

Review

Coffee Pulp Recycling in Coffee Cultivation: Agronomic Effects and Bean Quality Responses

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Abstract

Improper disposal of coffee-processing by-products can cause environmental pollution, greenhouse gas emissions, and resource loss, whereas their reuse in coffee plantations may support sustainable production. This review systematically examines the material properties, stabilization methods, field application pathways, agronomic effects, quality responses, and environmental risks of coffee-pulp-type by-products in cultivation. Relevant studies published up to June 2026 were retrieved from Web of Science, Scopus, ScienceDirect, SpringerLink, Google Scholar, and CNKI and qualitatively synthesized along the soil–plant–quality continuum. Current evidence suggests that properly stabilized materials, applied at appropriate rates, can improve soil organic matter, structure, water and nutrient retention, microbial activity, plant growth, photosynthesis, and crop yield in plantations. They may also indirectly influence green bean quality by regulating sugars, amino acids, chlorogenic acids, and caffeine. However, these effects depend strongly on material properties, maturity, application rate, coffee genotype, soil and climatic conditions, and management practices. Excessive or insufficiently decomposed materials may cause soil acidification, phytotoxicity, oxygen depletion, nutrient imbalance, and yield–quality trade-offs. Overall, recycling within plantations can turn processing waste into farm inputs, reinforce on-farm carbon and nutrient cycles, ease disposal burdens, and advance BCG and wider circular-economy principles in practice.

Keywords: coffee husk; coffee pulp; coffee-pulp-type by-products; composting; organic amendment; soil health; sustainable coffee cultivation

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1. Introduction

Coffee (*Coffea* spp.) is an economically important cash crop in tropical and subtropical regions and serves as a vital source of livelihood for smallholder farmers in many coffee-producing countries [1–3]. However, coffee processing generates substantial quantities of organic by-products: coffee pulp, which is generated during wet or semi-wet pro-

cessing, accounts for approximately 40–50% of the fresh coffee cherry weight [4,5]. In contrast, dry processing primarily generates coffee husk. These two materials differ in origin, moisture content, chemical composition, and decomposition behavior, and should therefore not be treated as one category in this review.

The compositional characteristics of coffee pulp constitute an important material basis for both its agricultural valorization potential and its environmental risks. Its beneficial components primarily include readily degradable carbohydrates such as soluble sugars and pectin, structural polysaccharides including cellulose and hemicellulose, as well as proteins, lipids, and mineral nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium [6,7]. Together, these components make coffee pulp potentially useful as an organic carbon source, a substrate for microbial metabolism, a composting feedstock, mulch material, a soil amendment, and a partial replacement for chemical fertilizers. The readily degradable carbon fraction provides substrates for microbial activity and nutrient transformation, while mineral nutrients participate in nutrient return and cycling within coffee plantations. Coffee pulp also contains bioactive compounds such as chlorogenic acids and flavonoids, although their agricultural effects are jointly constrained by compound type, concentration, and environmental conditions. Meanwhile, coffee pulp also contains caffeine, tannins, phenolic compounds, organic acids, and other substances with potential antinutritional or phytotoxic effects [8,9]. Fresh coffee pulp generally has high moisture, is naturally acidic, and therefore undergoes rapid fermentation after processing when untreated. When applied to soil in large quantities without prior treatment, particularly when concentrated in the main root zone of coffee plants, it may inhibit seed germination and root growth, disrupt soil microbial processes, and induce localized acidification, oxygen depletion, organic acid accumulation, and phytotoxicity [8,10]. If stockpiled in the open or discharged directly with processing wastewater, its rapid decomposition under high-temperature and high-humidity conditions may also generate organic-rich leachate and odorous gases, while releasing greenhouse gases such as methane and nitrous oxide. Leaching and surface runoff can further transport organic matter, nutrients, and bioactive compounds to adjacent soils and water bodies, thereby increasing the risk of agricultural non-point source pollution [6,11]. The “dual nature” of coffee pulp, characterized by the coexistence of beneficial nutrients and the dual nature of coffee pulp, arising from the coexistence of beneficial nutrients and potentially inhibitory compounds, explains both its agricultural utilization value and the limitations of direct field application in practice. Potentially inhibitory components both explain its agricultural utilization value and reveal the limitations of its direct field application. Therefore, coffee-pulp valorization should not mean simply applying untreated processing residues to farmland; instead, stabilization, phytotoxicity reduction, rate control, and balanced nutrient management should produce an agricultural input with more predictable safety and agronomic performance under field conditions and across diverse plantation environments over time when applied at appropriate rates.

Based on the above material distinction, this review focuses on coffee pulp generated from wet or semi-wet processing and its stabilized derivatives as the core research subjects. Given that the terminology for coffee pulp and coffee husk is not consistently used in the existing literature, and that some agricultural utilization studies involve both materials, this review appropriately incorporates comparative or supplementary evidence on coffee husk and other related by-products in the sections concerning material physico-chemical properties, stabilization treatments, field application pathways, and agronomic effects [7,10,12]. For findings on different materials, this review presents results wherever possible according to the specific material types reported in the original studies, avoiding the direct extrapolation of compositional characteristics and agronomic effects from coffee husk or other by-products to coffee pulp. In this review, coffee pulp recycling refers to the

sustainable management process by which coffee pulp and its stabilized derivatives, after appropriate treatment, re-enter the soil–plant system of coffee plantations through pathways such as surface mulching, controlled soil incorporation, application of composted materials, or partial substitution of chemical fertilizers. Coffee pulp can be stabilized through composting, aerobic co-composting, fermentation, vermicomposting, or carbonization to reduce its perishability and potential phytotoxicity, and to regulate its nutrient release characteristics. The actual effects of different treatment and application methods depend on material composition, degree of maturity, application rate and placement, as well as background soil fertility and local hydrothermal conditions. Fresh coffee pulp that has not been adequately composted should not be applied in large quantities or over extended periods, nor should it be directly concentrated in the main root zone of coffee plants [13].

In the coffee pulp recycling system, the coffee plant is the core of cultivation management, while soil serves as the primary medium through which roots obtain water and mineral nutrients. Soil amelioration is not the ultimate goal of recycling, but rather an important pathway to support plant nutrition, physiological metabolism, yield formation, and potential quality modulation. In addition to nutrient uptake through roots, coffee plants may also receive supplemental specific nutrients via foliar fertilization when root uptake is constrained or during critical growth stages. However, foliar fertilization has limited nutrient loading capacity and duration, and cannot replace long-term rhizosphere nutrient supply, soil organic matter management, or the sustained fertilization effect provided by coffee pulp recycling [14]. Long-term intensive monoculture is typically associated with soil degradation and nutrient imbalance. Coffee plants continuously remove mineral nutrients from the soil through successive growth and repeated harvest cycles; excessive reliance on chemical fertilizers coupled with neglect of organic matter replenishment and soil biotic community maintenance may lead to declines in soil organic matter, intensification of acidification, nutrient imbalances, reduced aggregate stability, and decreased microbial diversity [15]. This, in turn, can weaken soil water and nutrient retention capacity, restrict root growth and nutrient uptake, and further affect plant nutritional status, photosynthetic performance, yield stability, and green bean quality [16]. Following stabilization treatments, coffee pulp can be used as mulching material, soil organic amendment, or partial substitute for chemical fertilizers [17]. Its readily degradable carbon fraction can influence soil extracellular enzyme activities and the transformation processes of carbon, nitrogen, and phosphorus under suitable conditions [18]. During the decomposition of the material, organically bound nitrogen and phosphorus can be gradually released through mineralization, while nutrients with greater solubility such as potassium may enter the soil available nutrient pool more rapidly. The rate and availability of nutrient release are jointly regulated by material type, degree of maturity, application rate, soil properties, and environmental conditions [19]. Coffee-pulp recycling may also ease root-growth constraints and improve plant access to water and nutrients by enhancing soil structure, water-holding capacity, nutrient availability, and biological activity in soils. Following improved plant nutrition and growth, root biomass, root exudates, and litter inputs may increase accordingly, providing soil microorganisms with greater plant-derived carbon and potentially further influencing soil aggregate formation and organic carbon accumulation [20]. Thus, coffee-pulp recycling may create a feedback loop: improved soil conditions enhance root nutrient uptake, plant growth, carbon fixation, and ultimately plant-derived organic matter inputs to soils. Therefore, its agronomic effects should be understood as synergistic interactions among soil functions, plant nutrition, physiological responses, and yield formation, rather than a unidirectional soil amelioration process.

The potential effects of coffee pulp recycling on coffee quality are more indirect. Its treatment and field application primarily act upon the soil and rhizosphere environment,

which may subsequently influence root nutrient uptake, plant physiological status, source–sink partitioning, and fruit development, thereby altering the accumulation of flavor precursor compounds in green coffee beans, including sucrose, lipids, amino acids, chlorogenic acids, caffeine, and organic acids [17,21–23]. These components participate in reactions such as caramelization, the Maillard reaction, Strecker degradation, and pyrolysis during roasting, affecting sensory attributes including aroma, acidity, sweetness, bitterness, and body [24,25]. However, changes in green bean chemical composition are not equivalent to a direct improvement in cupping quality. The precursor compounds formed during the cultivation stage are further modulated by fruit harvest maturity, fermentation, drying, storage, roasting, and extraction conditions. Therefore, the relationship between coffee pulp recycling and final sensory quality is multi-step, indirect, and condition-dependent. This review outlines a pathway from field management to cup quality: pulp treatment methods shape soil-rhizosphere interactions, which influence vegetative growth and secondary metabolite accumulation in green beans; these biochemical changes persist during roasting and through thermally induced transformations, ultimately influencing sensory evaluation outcomes in the final brewed coffee cup for consumers. A complete causal link from coffee-pulp application to final cup quality remains unestablished; its direction and magnitude are further modulated by variety, environment, fruit maturity, and processing conditions.

Although coffee pulp recycling holds potential significance for soil management, plant nutrition, yield stability, and waste valorization, existing research suffers from three major deficiencies. First, the terminology and material classification of coffee pulp, coffee husk, and their processed derivatives are inconsistent across studies. In particular, some studies fail to clearly distinguish between coffee pulp generated from wet or semi-wet processing and coffee husk from dry processing, which may lead to the compositional characteristics, decomposition behavior, and agronomic effects of different materials being conflated, thereby reducing the comparability of results. Second, there is a lack of unified quantitative evaluation standards for the maturity requirements, appropriate application rates, fertilizer substitution ratios, applicable conditions, and environmental risk thresholds for coffee pulp. Third, the causal pathway from soil and rhizosphere responses to plant physiology, flavor precursor accumulation, roasting reactions, and final cup quality remains unclear. To address these research gaps, this review focuses on the recycling of coffee pulp and its stabilized derivatives in coffee cultivation, systematically synthesizing their compositional characteristics, potentially antinutritional and phytotoxic constituents, stabilization and phytotoxicity mitigation techniques, field application pathways, and their effects on soil properties, plant nutrition, physiological performance, yield formation, and green bean chemical composition. Coffee husk and other related processing by-products are discussed only when they provide direct comparative or supplementary evidence for the material differentiation, treatment methods, or agronomic effects of coffee pulp, with specific material types clearly indicated according to the original studies to avoid substitution or extrapolation of findings across different materials. This review pays particular attention to the dose- and environment-dependent nature of the relevant effects, as well as risks including soil acidification, phytotoxicity, localized hypoxia, temporary nitrogen immobilization, and nutrient imbalances. It seeks to support the safe utilization and valorization of coffee pulp and inform sustainable management of circular agriculture and coffee production systems.

2. Literature Search Strategy

This review adopts a narrative review approach combined with a structured literature search. Relevant literature was collected from Web of Science, Scopus, ScienceDirect, SpringerLink, Google Scholar, and CNKI, with the search conducted up to June 2026. The search terms included “coffee pulp”, “coffee by-products”, “composting”, “biochar”, “soil amendment”, “nutrient cycling”, “microbial community”, “enzyme activity”, “coffee yield”, and “coffee quality”, together with their Chinese equivalents where appropriate.

Studies were included if they examined coffee pulp, coffee husk, mucilage, silverskin, composted residues, or biochar as agricultural amendments, or if they reported their effects on soil properties, plant physiology, nutrient uptake, coffee yield, green bean quality, or environmental risks. Studies focusing solely on food processing, beverage extraction, pharmaceutical utilization, or industrial valorization were excluded when they had no direct relevance to soil management, crop production, or coffee plantation management. However, representative studies on alternative valorization pathways were included for comparative assessment of their resource efficiency, technical requirements, economic feasibility, and circular-economy relevance.

The extracted information included material type, treatment method, application pathway and rate, experimental conditions, soil type, coffee species or cultivar, measured indicators, and main findings. The evidence was then synthesized along the “soil–plant–quality” pathway. This review was not designed as a systematic review or meta-analysis; therefore, no formal risk-of-bias assessment or quantitative effect-size synthesis was conducted. Because the included studies differed substantially in material type, treatment method, application rate, soil and climatic conditions, coffee genotype, and experimental duration, the results were summarized qualitatively rather than through meta-analysis. Reported numerical values are therefore used only to illustrate response trends under specific experimental conditions and should not be interpreted as universally applicable estimates.

3. Material Basis of Coffee-Pulp-Type By-Products as Agricultural Organic Amendments

Coffee pulp is one of the largest agricultural by-products generated during coffee processing and has dual characteristics of resource utilization potential and environmental risk. In terms of its beneficial attributes, coffee pulp is rich in organic carbon, mineral nutrients, and degradable organic components, giving it potential as a soil amendment, a raw material for organic fertilizer production, and a carrier for nutrient cycling. In terms of risk, differences in material source, processing method, moisture content, C/N ratio, and the concentrations of bioactive compounds such as phenolics and caffeine directly affect the safety of its direct return to soil or broader agricultural utilization. Therefore, before discussing the agricultural recycling pathways of coffee pulp, it is necessary to clarify its conceptual boundaries, material types, and physicochemical properties. This provides the material basis for subsequent analyses of field return, composting, organic fertilizer substitution, and soil improvement effects.

3.1. Definition and Classification of Coffee-Pulp-Type By-Products

The coffee cherry is anatomically composed, from the outside to the inside, of the exocarp, mesocarp or pulp, mucilage layer, endocarp or parchment, silverskin, and endosperm [26]. In the coffee processing sector, two major categories of by-products are frequently confused: fresh pulp (coffee pulp) removed during wet or semi-wet processing, and the composite husk (coffee husk) obtained through dry processing after whole-fruit drying and dehulling. Although the existing literature often loosely groups both under

the umbrella term “coffee-pulp-type by-products,” they differ substantially in processing origin, moisture content, fiber composition, and nutrient composition [7,12]. In this review, coffee pulp and its stabilized derivatives are the primary focus, whereas coffee husk is included only as comparative or supplementary evidence when it provides relevant information on material properties, treatment methods, or agronomic effects (Table 1). Findings are presented according to the specific material types reported in the original studies to avoid inappropriate substitution or extrapolation between coffee pulp and coffee husk. Where the original literature does not clearly distinguish the material type, the umbrella term “coffee-pulp-type by-products” is used cautiously for integrated discussion.

3.2. Physicochemical Properties of Coffee-Pulp-Type By-Products

Coffee pulp is rich in organic matter and degradable carbon sources, and its physicochemical properties provide a basis for assessing its suitability for different agricultural uses, including field return, mulching, composting, and organic fertilizer substitution. In terms of chemical composition, coffee pulp contains relatively high proportions of organic carbon, soluble sugars, pectin, cellulose, hemicellulose, and lignin, and is also rich in mineral nutrients such as potassium, calcium, magnesium, and phosphorus, as well as crude protein. For a comprehensive assessment of its nutritional potential, coffee pulp composition should be considered in four complementary categories: (i) proximate composition, including moisture, dry matter, ash, crude protein, crude lipid, and total carbohydrates; (ii) readily degradable and structural carbohydrates, including soluble sugars, pectin, cellulose, hemicellulose, and lignin; (iii) macro- and micronutrients, including N, P, K, Ca, Mg, S, Fe, Mn, Zn, and Cu; and (iv) bioactive or potentially limiting compounds, including caffeine, total phenolics, tannins, chlorogenic acids, and low-molecular-weight organic acids. However, by-products generated from different processing methods differ in composition and decomposition characteristics. Coffee pulp produced during wet processing generally has a high moisture content and strong degradability. Getachew et al. measured the physicochemical properties of Ethiopian coffee pulp and its ensiled material and reported that coffee pulp had a moisture content of 83.94%, an organic carbon content of 51.96%, a total Kjeldahl nitrogen content of 2.03%, a C/N ratio of 25.60, and a pH of 4.80. These values indicate that fresh coffee pulp is a high-moisture, slightly acidic organic material that is readily transformed by microorganisms [8,27]. By contrast, coffee husk produced during dry processing usually has a higher carbon content and a greater proportion of lignocellulosic components. Elemental analysis studies have shown that the total carbon content of coffee husk generally ranges from 40% to 55%. For example, Bonilla et al. reported a carbon content of 44.52% in Colombian coffee husk, Setiawan et al. reported a carbon content of 44.00% in Arabica coffee husk, and Duque-Dussán et al. reported a carbon content of 51.11% in Cenicafé 1 coffee husk. These findings suggest that coffee husk is a carbon-rich organic residue, although its specific carbon content varies considerably depending on cultivar, production area, processing method, drying degree, and analytical basis [27–29]. Coffee pulp typically exhibits an acidic pH, ranging from approximately 4.0 to 4.8, and contains bioactive components such as total phenolics and caffeine [8,9]. Tannins, chlorogenic acids, and low-molecular-weight organic acids may also be present. Although some phenolic compounds have potential value-added properties, elevated concentrations of caffeine, tannins, phenolics, and organic acids may inhibit seed germination, root elongation, or selected microbial processes [30]. These acidic and bioactive components may affect the safety of direct soil application and are important factors determining whether composting, fermentation, or other stabilization treatments are required before field use. Therefore, the C/N-related risks of coffee pulp return should not be generalized. Fresh coffee pulp produced during wet or semi-wet processing usually has a

relatively low C/N ratio, and its main risks are more closely associated with high moisture content, rapid fermentation and spoilage, acidic substances, and short-term stress caused by allelopathic components such as phenolics and caffeine. In contrast, coffee husk produced during dry processing, dried mixed residues, or materials co-applied with high-carbon bulking agents such as straw or sawdust may have a relatively high C/N ratio. During early decomposition, these materials may increase microbial competition for soil-available nitrogen and lead to temporary nitrogen immobilization. Accordingly, the field application strategy and risk control of coffee pulp and related by-products should be evaluated according to material source, processing method, moisture content, C/N ratio, lignocellulosic composition, and degree of decomposition.

With respect to soil improvement functions, the organic matter and structural carbon in coffee pulp can promote aggregate formation, improve pore structure, and enhance water retention capacity, while the mineral elements it contains—including potassium, calcium, and magnesium—can also provide important supplements for crop nutrient cycling. Previous studies have reported that coffee pulp can reach a K₂O content of approximately 3.60%, whereas its calcium and magnesium contents are strongly influenced by origin, processing method, and analytical basis [31]. Nevertheless, coffee pulp also contains bio-active substances such as phenolics, tannins, and caffeine, which at higher concentrations may inhibit seed germination, root growth, or soil microbial activity. Given its acidic pH, fresh pulp is unsuitable for long-term, large-scale direct field return; it is more appropriately applied after composting, fermentation, vermicomposting, or carbonization [4]. Understanding the organic carbon content, C/N ratio, lignocellulosic composition, mineral nutrient status, pH, and phenolic/caffeine levels of coffee pulp is essential for scientifically evaluating its agricultural utilization value and risk control strategies.

3.3. Agricultural Potential of Coffee-Pulp-Type By-Products

Based on the aforementioned physicochemical properties, the agricultural utilization potential of coffee pulp is primarily realized in four aspects: organic carbon inputs, replenishment of mineral nutrients, provision of microbial carbon sources, and improvement of soil structure. In particular, its high potassium content gives it a distinct advantage in potassium replenishment and internal nutrient cycling in coffee plantations [32]. The soluble sugars, pectin, cellulose, and hemicellulose fractions in coffee pulp serve as important carbon sources for soil microbial activity, thereby promoting microbial metabolism, soil enzyme activity, and the decomposition and transformation of organic matter [33]. Organic N and a fraction of P in coffee-pulp-derived materials may become progressively available through microbial decomposition and mineralization, whereas K is generally released more rapidly because it is not structurally incorporated into organic carbon compounds [19]. Cellulose and hemicellulose are progressively decomposed during composting, while lignin is comparatively resistant to microbial degradation and therefore contributes more strongly to the residual structural carbon of mature compost [34]. At the same time, the organic matter and humic products formed during the decomposition process help improve soil aggregate structure, porosity, and water and nutrient retention capacity, thereby creating a more suitable rhizosphere environment for coffee root growth and nutrient uptake [35]. Thus, coffee pulp not only contributes to nutrient replenishment but also exhibits potential for soil amelioration and rhizosphere ecological regulation.

However, the agronomic effects of coffee pulp recycling are not always positive and depend on material source, processing method, moisture content, C/N ratio, maturity, application rate, soil fertility, and regional hydrothermal conditions. Fresh coffee pulp has a high moisture content and contains compounds such as phenolics, caffeine, organic acids, and soluble salts. If large quantities are returned to the soil without proper treatment, this

may lead to problems such as rapid fermentation and decay, allelopathic inhibition, acidification, nutrient imbalance, or the proliferation of pathogenic microorganisms. Therefore, the agricultural utilization of coffee pulp should be prioritized through stabilization and detoxification via methods such as composting, fermentation, vermicomposting, or carbonization, with the choice of an appropriate utilization pathway determined in conjunction with soil nutrient status and the nutrient requirements of coffee crops [36]. For solid-state treatment, aerobic windrow composting and co-composting with other organic wastes or structural conditioners are already well-established processes. A typical operational procedure involves composting coffee pulp alone or co-composting it with source-separated urban organic wastes in manually turned windrows, with individual piles of approximately 1 m³ and a composting period of three months. During composting, the moisture content is maintained at 50–60%, with turning two to three times per week during the first two months and once per week during the maturation phase. Maturity is comprehensively evaluated using indicators including temperature, pH, electrical conductivity, C/N ratio, and seed germination rate [10]. For liquid fertilizer production, a temperature-controlled fermentation process has also been reported. Fresh coffee pulp and molasses were mixed at a 1:1 ratio and fermented for seven days. After fermentation, the liquid fraction was extracted by pressing and diluted to 15–45 mL/L for soil drenching or foliar application [34]. Notably, however, this process was tested on cabbage seedlings rather than coffee plants; it should therefore be viewed as a technical reference rather than a directly transferable protocol for coffee plantation application. Therefore, the appropriate valorization pathway should be selected according to initial material characteristics, target fertilizer product type, soil nutrient status, crop requirements, and achievable process control levels, while the specific application method, application rate, substitution ratio, and associated risk boundaries still require category-based evaluation and quantitative definition in combination with subsequent field application practices and local management conditions.

Table 1. Comparison of key physicochemical properties, utilization suitability, and potential risks between coffee pulp and coffee husk as agricultural organic amendments.

Property/Aspect	Coffee Pulp	Coffee Husk	Implications for Agricultural Use	References Cited
Processing origin	Produced during wet or semi-wet processing, when the pulp is removed from fresh coffee cherries.	Produced during dry processing after whole-fruit drying and dehulling; it is a composite outer-fruit residue.	The two materials should not be treated as interchangeable because their origin and physical properties differ.	[7,12,26]
Main anatomical association	Primarily associated with the mesocarp/pulp fraction of the coffee cherry.	Derived from the dry-processed whole fruit and may include multiple outer-fruit layers.	Material identity should be specified in studies and field recommendations.	[26]
Moisture content	Typically high; Ethiopian coffee pulp was reported to have 83.94% moisture. Fresh pulp is prone to rapid fermentation and spoilage.	Generally lower moisture than fresh pulp because it is produced after fruit drying.	Fresh pulp usually requires drying, pre-composting, fermentation, or other stabilization before extensive field application; husk is easier to handle and store.	[7,8,12,27]
Organic carbon and degradability	Rich in organic matter, soluble sugars, pectin, cellulose, hemicellulose, and other readily de-	Carbon-rich, with total carbon generally reported in the range of 40–55%; contains a relatively greater	Pulp can rapidly stimulate microbial activity but can also ferment quickly. Husk is generally more persistent	[8,27–29,33,34]

	gradable carbon fractions. Reported organic carbon content: 51.96% in one Ethiopian pulp sample.	proportion of structural lignocellulosic carbon.	and better suited to structural uses or co-composting.	
C/N ratio	Usually relatively low in fresh pulp from wet or semi-wet processing; one reported value was 25.60.	May have a relatively higher C/N ratio, especially for dry husk or when mixed with straw/sawdust.	Fresh pulp risks are mainly linked to moisture, acidity, rapid fermentation, and phytotoxic compounds. High-C/N husk or dry mixtures may temporarily immobilize soil N during early decomposition.	[8,27]
pH and acidity	Typically acidic, approximately pH 4.0–4.8; one reported value was pH 4.80.	The supplied text does not provide a specific pH range for husk.	The acidic nature of fresh pulp increases the need for controlled application and stabilization before field return.	[8,9,27]
Major nutrient characteristics	Contains N, P, K, Ca, Mg, and other nutrients; noted for relatively high potassium. Coffee pulp may reach approximately 3.60% K ₂ O.	Contains nutrients, but the supplied text emphasizes its carbon and lignocellulosic composition rather than specific nutrient concentrations.	Both can contribute to nutrient cycling, but pulp has particular potential as a K-containing organic input. Nutrient composition should be analyzed locally before determining fertilizer substitution rates.	[19,31,32]
Bioactive and potentially inhibitory compounds	May contain caffeine, total phenolics, tannins, chlorogenic acids, and low-molecular-weight organic acids.	The supplied text indicates lower concentrations of inhibitory compounds relative to pulp in the composting context, but gives no quantitative values.	High concentrations of pulp-derived phenolics, tannins, caffeine, and organic acids may inhibit germination, root elongation, and some microbial processes.	[8,9,30]
Main direct-return risks	Rapid fermentation, spoilage, localized oxygen depletion, acidification, allelopathic effects, nutrient imbalance, and possible pathogen proliferation when applied excessively or while insufficiently stabilized.	Possible temporary N immobilization during decomposition if the material has a high C/N ratio and high lignocellulosic content.	Fresh pulp should not be used for long-term, high-rate direct return without treatment. Husk should be managed with attention to decomposition rate and N balance.	[4,30,36]
Suitability for mulching	Less suitable as thick fresh mulch because of high moisture and rapid decomposition; better used after drying or partial stabilization.	More suitable for surface mulching because it is drier and contains more structural carbon.	Husk is generally more appropriate for a persistent physical mulch, whereas pulp is better stabilized before use.	[7,12]
Suitability for composting	Highly suitable after moisture and aeration management. Soluble sugars and pectin support early microbial activity and pile heating.	Suitable as a structural, carbon-rich compost material; can help improve pile porosity when co-composted with wetter substrates.	Pulp composting requires moisture control and adequate aeration; husk can function as a bulking or structural component.	[10,34,36]
Recommended utilization direction	Composting, co-composting, fermentation, vermicomposting.	Surface mulching, composting, co-composting.	Management decisions should be based on material origin, moisture content, C/N	[4,10,36]

ing, carbonization, or controlled application after stabilization.

and controlled soil incorporation.

ratio, lignocellulosic composition, maturity, soil conditions, and crop nutrient demand.

4. Major Recycling Pathways of Coffee-Pulp-Type By-Products in Agriculture

Having clarified the physicochemical properties and agricultural utilization potential of coffee pulp and husk-derived by-products, we can now examine their specific recycling pathways in diverse coffee production systems. Because coffee pulp, coffee husk, and dried by-products differ in moisture content, organic carbon composition, C/N ratio, degree of decomposition, and the concentrations of inhibitory compounds, their suitable field application methods also differ [37]. Different recycling pathways vary in input cost, operational complexity, nutrient release characteristics, soil improvement effects, and environmental risk control. Therefore, coffee pulp recycling in coffee cultivation should not rely on a single application pathway. Instead, diversified recycling strategies, including direct surface mulching, crushing and soil incorporation, composting, co-composting, and partial organic fertilizer substitution, should be developed according to material type, field conditions, and management objectives (Figure 1, Table 2).



Figure 1. Major pathways for the resource utilization of coffee pulp byproducts in coffee cultivation.

Table 2. Summary of major recycling pathways for coffee-pulp-type by-products in coffee cultivation, including applicable materials, operational requirements, agronomic effects, and associated risks.

Recycling Pathway/Recycling Mode	Applicable Materials	Main Operation and Management Requirements	Main Agronomic Effects/Advantages	Main Risks and Precautions	References Cited
Direct field return	Coffee husk, dried pulp, partially decomposed pulp, composted pulp; only limited quantities of fresh pulp	Apply in inter-rows, around tree basins, or through shallow incorporation. Application rate, layer thickness, and placement should be controlled, particularly for fresh wet pulp.	Returns organic matter and nutrients to the plantation; reduces disposal requirements; supports internal recycling of processing residues.	Fresh pulp has high moisture content and readily ferments; excessive direct application may cause spoilage, anaerobic conditions, acidification, and pathogen proliferation.	[37]
Surface mulching	Preferably dry coffee husk, dried pulp, or semi-rotted pulp	Apply between coffee rows or around trees; maintain mulch depth generally at 5–10 cm. Reduce thickness under high rainfall, poor drainage, or high disease pressure. Keep mulch away from the trunk and primary root zone.	Reduces rain splash, runoff, and erosion; conserves soil water; buffers soil temperature; suppresses weeds; gradually returns organic matter and mineral nutrients to topsoil. Reported erosion reduction: 40–70%; soil-water increase: 15–30%; daytime maximum-temperature reduction: ca. 3–8 °C; weed biomass reduction: 50–80%.	Thick layers of fresh pulp may create localized anaerobic conditions, organic-acid accumulation, acidification, and pathogen risks. Fresh pulp is less suitable than dry or partially decomposed materials.	[38,39]
Crushed soil mixing	Coffee husk, dried pulp, dried mixed residues, and partially decomposed pulp	Crush material and mix with surface soil; apply through shallow furrows, strips, or holes between rows or near—but preferably outside—the canopy drip line.	Greater soil–material contact promotes microbial decomposition and nutrient release; shallow burial reduces loss of material by rainfall runoff or wind.	Avoid incorporating large amounts of fresh wet pulp into the main root zone, as rapid fermentation may cause oxygen depletion, organic-acid accumulation, and root stress. Pre-compost, dry, or partially decompose fresh pulp before incorporation.	[40–42]
Shallow-buried trench/furrow application	Mainly coffee husk, dried pulp, and partially decomposed pulp	Apply in shallow trenches or furrows in inter-row areas or outside the main rooting zone; avoid concentrated application near major roots.	Improves retention of material in the field and facilitates gradual decomposition and nutrient release.	Improper placement of fresh pulp may lead to localized phytotoxicity, oxygen deficiency, and root inhibition.	[40–42]
Single-material aerobic composting	Coffee pulp and coffee husk; coffee pulp may also	Use manually turned aerobic piles; maintain moisture at about 50–60%. Suggested initial	Stabilizes organic matter; reduces phytotoxicity; improves safety for soil application; supports slow	Excessive moisture or insufficient aeration may cause anaerobic decomposition, odor,	[10,43–47]

	be composted alone	C/N ratio: ca. 25:1–35:1; maintain a thermophilic stage above 55 °C. Assess maturity using temperature, pH, EC, C/N ratio, and seed-germination tests.	nutrient release and rhizosphere improvement. Coffee pulp may be composted for approximately three months under suitable management.	and leachate. Immature compost can cause root inhibition and N immobilization. Coffee-husk results should not be directly extrapolated to coffee pulp.	
Co-composting with manure	Coffee pulp or husk + livestock manure	Adjust mixture according to moisture, C/N ratio, and composting method. Manure supplements N and P and provides microbial inocula.	Improves nutrient balance, microbial activity, pile heating, nutrient transformation, and humification.	Excess manure or poor moisture/aeration management may still lead to odor, nutrient loss, or anaerobic conditions.	[10,48]
Co-composting with structural bulking agents	Coffee pulp + straw, sawdust, coconut coir, or similar bulking materials	Use structural materials to increase porosity and regulate moisture; adjust proportions according to pulp moisture content and material characteristics.	Improves aeration and pile structure; reduces the likelihood of anaerobic decomposition of wet pulp.	No fixed mixing ratio is suitable for all materials; ratios should be adjusted case by case.	[10,49]
Partial substitution of chemical fertilizer with coffee-pulp-derived organic fertilizer	Mature coffee-pulp compost, fermented products, or commercially processed organic fertilizer	Combine organic fertilizer with mineral fertilizer to provide both readily available nutrients and longer-term organic-matter inputs. In some studies, 25–50% of chemical N was replaced by coffee-pulp compost.	Increases soil organic matter; improves soil structure, water retention, nutrient retention, and microbial activity. Under specific conditions, yields increased by 5–15%.	Yield and fertilizer-substitution effects are site-specific; reported substitution ratios and yield responses should not be treated as universal recommendations.	[17,50,51]
In situ fermentation/field-side conversion	Fresh or partially decomposed coffee pulp	Includes field-side stacking, mulching fermentation, furrow fermentation, and small-scale anaerobic fermentation. Maintain an application distance of at least 30–50 cm from roots after partial decomposition; allow a safety interval of at least 2–4 weeks before direct root contact.	Low-cost on-site option; reduces transport costs and promotes recycling of processing residues within coffee farms.	Less controllable than standardized composting; may cause odor, leachate, incomplete decomposition, and localized root toxicity if poorly managed.	[37,39]

4.1. Direct Field Return, Surface Mulching, and Fermented Liquid Fertilizer

Direct field return of coffee-pulp-type by-products includes inter-row application, surface mulching, and shallow incorporation of coffee husk, dried pulp, partially decomposed pulp, composted pulp, or limited amounts of fresh pulp. Among them, dry-processed coffee husks exhibit lower moisture content and higher structural carbon content, making them more suitable as a covering mulch applied between coffee rows or around

tree basins. In contrast, fresh coffee pulp produced by wet processing has high moisture content and is prone to fermentation and spoilage; when returned directly to the field in large quantities as an organic amendment, the application rate, layer thickness, and placement must be carefully controlled [31,38].

Surface mulching is one of the most direct ways of returning coffee pulp to the field. Its core ecological functions include soil and water conservation, microclimate regulation, weed suppression and nutrient return. Several organic mulching studies have reported that mulch can reduce rain splash and surface runoff, decreasing soil erosion by 40–70%, with particular suitability for sloped coffee plantations and areas with high rainfall intensity [39,40]. Concurrently, the soil cover layer suppresses soil moisture evaporation and buffers soil temperature fluctuations. In hot-dry seasons or in production regions with limited water-holding capacity, it can increase soil water content by 15–30%, reduce daytime maximum temperatures by approximately 3–8 °C, and attenuate the diurnal temperature range by about 1–3 °C, thereby alleviating drought and heat stress [40].

The shading and physical barrier effects of mulch can suppress weed germination. Similarly, studies on mulching herbaceous crops such as mint have shown that weed biomass can be reduced by 50–80%, thereby reducing the labor required for weeding. As the mulch gradually decomposes, organic matter and mineral nutrients are slowly released into the topsoil, promoting the accumulation of soil organic carbon and nutrient cycling. Because fresh coffee pulp has a high moisture content and contains readily degradable organic compounds, direct thick-layer mulching with fresh pulp may create localized anaerobic conditions, organic acid accumulation, acidification, and pathogen proliferation [41]. Therefore, it is more suitable to use dry pulp, semi-rotted pulp or coffee husk. Mulching depth should generally be maintained at 5–10 cm. On sites with heavy rainfall, poor drainage, or high disease pressure, reduce the mulch depth accordingly, and ensure the material does not contact the tree trunk or the primary root zone [42].

In addition to solid field return and surface mulching, the high moisture content and soluble components of fresh coffee pulp provide the basis for its conversion into fermented liquid organic fertilizer. In one reported process, fresh coffee pulp was mixed with molasses at a 1:1 ratio and fermented for seven days. The liquid fraction was subsequently extracted by pressing, diluted to 15–45 mL L⁻¹, and applied to cabbage seedlings through soil drenching or foliar spraying. This approach may facilitate the recovery and application of soluble nutrients from coffee pulp while reducing the volume of solid material requiring field disposal. Nevertheless, because the reported process was evaluated using cabbage seedlings rather than coffee plants, the 1:1 mixing ratio, seven-day fermentation period, and dilution rates should be regarded as preliminary process parameters rather than direct recommendations for coffee plantations. Before field application, the fermented liquid product should be evaluated for pH, electrical conductivity, nutrient composition, residual caffeine and phenolic compounds, microbial safety, storage stability, and crop-specific dilution and application requirements. Therefore, fermented coffee-pulp liquid fertilizer represents a promising but insufficiently validated pathway that requires further testing under coffee-plantation conditions.

4.2. Crushed Soil Mixing and Shallow-Buried Trench Application Model

Crushing and soil incorporation represent a low-cost utilization approach positioned between direct mulching and compost application. In this practice, coffee pulp, coffee husk, or dried mixtures are typically crushed and then mixed with the surface soil, or shallow-buried through furrow, strip, or hole application along inter-rows or near the drip line of coffee tree canopies [43]. Compared with surface mulching alone, crushing increases the contact area between the material and soil, thereby promoting microbial de-

composition and nutrient release [44]. Simultaneously, shallow burial or furrow application reduces the risk of material being washed away by rainfall or dispersed by wind, thereby improving the efficiency of organic matter entry into the soil [45]. This mode is suitable for coffee husk, dried pulp, or partially decomposed pulp materials. In contrast, the incorporation of large quantities of fresh, wet coffee pulp into the main root zone should be avoided. This is because fresh pulp contains high levels of soluble sugars, organic acids, phenolics, and caffeine; if rapid fermentation continues in soil, it may cause substantial localized oxygen depletion, organic acid accumulation, and root stress [46]. In practical applications, crushed materials should preferably be applied outside the canopy drip line or between rows, while concentrated placement in the main root zone should be avoided. For fresh coffee pulp, short-term pre-composting, drying, or partial decomposition should be conducted before soil incorporation or trench application.

4.3. Composting, Stabilization, and Matured Compost Application

Compost maturation is a key step in enhancing the safety of returning coffee pulp to soil and stabilizing its fertilization efficacy. Coffee pulp and coffee husk should be clearly distinguished because coffee pulp generally has higher moisture and more readily degradable compounds, whereas coffee husk is drier and richer in lignocellulosic components. The greater prevalence of coffee-husk composting in the literature is partly due to its lower moisture content and lower concentrations of inhibitory compounds, which make it easier to handle and less prone to rapid acidification and odour generation during processing. Therefore, results from coffee-husk composting should be used only as comparative evidence and not directly extrapolated to coffee pulp. The soluble sugars, pectin, and readily degradable organic carbon in the coffee pulp provide ample substrates for early microbial activity in the compost, promoting pile temperature rise and the transformation of organic matter [47,48]. Coffee pulp has been successfully composted alone or co-composted with organic wastes in manually turned aerobic piles for approximately three months, with moisture maintained at about 50–60% and maturity assessed using temperature, pH, electrical conductivity, C/N ratio, and seed-germination responses [10]. Commonly recommended composting conditions include an initial C/N ratio of approximately 25:1–35:1, moisture content around 50–60%, and a thermophilic phase above 55 °C. However, the optimal duration and maturity criteria depend on pile size, aeration, bulking agents, and the initial moisture and phenolic/caffeine contents of the material [49,50].

Properly managed pile-based composting can reduce inhibitory compounds in coffee pulp, including organic acids, phenolics, and caffeine, while lowering the risks associated with pathogens and weed seeds. It can also improve material stability and application safety by promoting organic matter transformation and reducing phytotoxicity. The key parameters controlling the composting process include moisture content, aeration conditions, pile temperature, and composting duration. Excessive moisture content or insufficient aeration can promote anaerobic decomposition, leading to odor emissions and leachate production. Insufficient composting duration may also result in root inhibition or nitrogen immobilization after the material is applied to soil [51]. Fully matured coffee pulp compost is therefore more suitable for use as a soil amendment or basal fertilizer in coffee plantations, where it can contribute to organic matter replenishment, slow nutrient release, and improvement of the rhizosphere environment.

4.4. Co-Composting and Organic Fertilizer Substitution for Land Application

During single-material coffee pulp composting, high moisture content, insufficient aeration, and nutrient imbalance may limit composting efficiency and the stability of fertilizer effects. Co-composting is an important strategy for addressing these limitations

[10]. The combination of coffee pulp or husk with organic materials such as livestock manure, straw, sawdust, and coconut coir can regulate the C/N ratio, moisture content, and pore structure of the compost pile, thereby improving aerobic conditions and promoting microbial decomposition and humification. Among these, the addition of livestock manure supplements nitrogen and phosphorus sources, enriches microbial resources, and enhances pile heating and nutrient transformation capacity [52]. In contrast, structural bulking agents such as straw and sawdust can increase pile porosity, improve aeration, and reduce the risk of anaerobic conditions during the composting of wet coffee pulp [53]. Therefore, the proportions in co-composting should not follow a fixed standard but should be dynamically adjusted according to pulp moisture content, C/N ratio, properties of auxiliary materials, and composting method. After composting, fermentation, or commercial processing, coffee pulp can be used as an organic nutrient source to partially substitute chemical fertilizers. The combined application of coffee pulp-derived organic fertilizer and chemical fertilizers can provide readily available nutrients while increasing organic matter input, improving soil structure, enhancing soil water and nutrient retention, and stimulating microbial activity [17,54]. In some field studies, replacing 25–50% of chemical fertilizer nitrogen with coffee-pulp compost was associated with a reported 5–15% overall yield increase under specific soil, climatic, and management conditions. These values should therefore be interpreted as context-specific observations rather than universal recommendations [17,55].

For smallholder farmers and coffee estates, in situ fermentation or conversion provides a low-cost, on-site approach that reduces costs associated with pulp transportation and enables internal recycling of processing by-products within coffee plantations locally. Common practices include field-side stacking, mulching fermentation, furrow fermentation, and small-scale anaerobic fermentation [38]. This pathway requires careful control of decomposition degree, moisture content, application distance, and safety interval. After partial decomposition, coffee pulp should preferably be kept at least 30–50 cm away from the root zone, and a safety interval of at least 2–4 weeks should be maintained before direct root contact, in order to reduce the risk of root inhibition caused by insufficiently decomposed materials. Because in situ fermentation offers less control than standardized industrial composting, poor management can cause odor emissions, leachate production, incomplete decomposition, and serious localized root toxicity in practice. Therefore, quantitative technical guidelines for this pathway need to be further developed [42].

5. Effects of Coffee-Pulp-Type By-Product Recycling on Soil Health and Nutrient Cycling

The recycling models described above surface mulching, soil incorporation, compost application, co-composting, and partial fertilizer substitution affect coffee production primarily through changes in soil physical, chemical, and biological properties. However, these effects differ among fresh pulp, dried husk, matured compost, and biochar because their moisture content, C/N ratio, decomposition rate, pH, and bioactive compound concentrations differ substantially. Therefore, the following section synthesizes the evidence according to the soil-root-plant-fruit continuum, while distinguishing material types wherever possible. The soil changes described above may further regulate root development, nutrient uptake, leaf photosynthetic performance, and yield formation. However, the direction and magnitude of their agronomic effects depend largely on amendment type and maturity, application rate, soil properties, rainfall, temperature, and drainage conditions.

5.1. Effects on Soil Physical Properties

Coffee-pulp-type by-products, particularly husk and fibrous residues, contain cellulose, hemicellulose, and lignin fractions that may contribute to soil structure improvement after decomposition. When applied as a surface mulch, these coarse-fiber organic residues primarily improve the topsoil micro-environment by reducing raindrop impact, decreasing evaporation, and buffering soil temperature extremes [23]. Under furrow application or soil incorporation, decomposition products and microbial-derived binding substances may further promote aggregate formation and stability, thereby decreasing bulk density and increasing porosity, aeration, and infiltration capacity. Fibrous particles can reduce soil particle packing and create additional pore space, while humified compounds and microbial binding agents formed during decomposition contribute to aggregate stabilization. In a 24-month soil-column experiment, the incorporation of an air-dried mixture of coffee pulp and husk at 5–20 t ha⁻¹ increased the fraction of retained soil water from 53% to 60% in a sandy Arenosol [44]. This improvement is not solely due to increased organic matter content but is also associated with the physical characteristics of the fibrous material and its decomposition dynamics. Previous studies have shown that under appropriate application rates, coffee pulp can reduce soil bulk density and improve water-holding capacity; however, the magnitude of these effects varies substantially with the degree of decomposition, soil texture, and experimental duration [56–58].

Under specific experimental conditions, moderate application of coffee-processing residues has been reported to reduce bulk density and improve porosity; however, the magnitude of change depends strongly on soil texture, residue type, application rate, and experimental duration [38]. Meanwhile, the application of biochar derived from coffee pulp at 8 or 16 t ha⁻¹ increased field water-holding capacity by 10–25% and improved soil aggregation to 96.84%, thereby creating a looser and more permeable physical space for coffee root development [58,59]. However, the results from biochar studies should not be directly extrapolated to fresh or composted pulp, as biochar has distinct physicochemical properties, including higher stability, different pH, and slower nutrient release rates. Under surface mulching, coffee pulp can form a protective layer on the soil surface, effectively reducing soil water evaporation and buffering sharp fluctuations in soil temperature [23]. Overall, the physical effects of coffee pulp return are strongly material- and environment-dependent, influenced by the application method, rate, and prevailing hydrothermal conditions.

5.2. Effects on Soil Chemical Properties

In addition to improving soil physical structure, coffee-pulp return also affects soil organic carbon accumulation, nutrient supply, and acid-base balance. The abundant organic matter in coffee pulp can promote the accumulation of soil organic carbon and soil organic matter through microbial decomposition and humification. In previous studies, the return of coffee-pulp-derived organic materials increased soil organic carbon stocks by 49.91% and soil organic matter content by 56.29% [60]. However, these values should be interpreted as responses under specific application rates, soil types, and experimental durations, rather than as universally applicable estimates. This gradual mineralization process contributes to continuous organic carbon input and the maintenance of soil fertility. In terms of nutrient supply, organic nitrogen in coffee pulp can be mineralized and released, thereby increasing soil alkali-hydrolyzable nitrogen. Organic phosphorus may be mobilized through phosphatase-mediated mineralization and organic acid chelation, which can activate fixed phosphorus in soil [60,61]; Compared with organically bound N and P, K in coffee-pulp-type materials may be released relatively rapidly during decomposition, although its availability still depends on soil exchange capacity, rainfall, leaching

risk, and the maturity of the applied material [44]. A specific study on coffee pulp mulching reported significant increases in soil available potassium (SAK) by 17.29% and alkali-hydrolyzable nitrogen (SAN) by 18.45% [62].

In one field study, a treatment combining 70% of the recommended inorganic fertilizer rate with a coffee-pulp-derived organic amendment (hereafter termed 0.7FR+O, where FR denotes fertilizer rate and O denotes organic amendment) improved several soil indicators compared with inorganic fertilization alone, including light-fraction organic carbon by 13.31–14.12% and microbial biomass carbon by 14.05% [55]. These results suggest that the combined application of coffee pulp-type organic materials and chemical fertilizers may be more favorable for coordinating organic carbon accumulation and mineral nutrient supply than application alone. However, the effects are highly dose- and environment-dependent, with outcomes depending on material maturity, C/N ratio, application rate, and background soil fertility [38]. Positive responses are more likely when well-composted or adequately stabilized materials are applied at moderate rates and combined with balanced nutrient management. In contrast, excessive use of fresh acidic pulp may increase the risks of soil acidification, phytotoxicity, and root stress, whereas high C/N or insufficiently decomposed residues may cause temporary nitrogen immobilization [63]. Therefore, coffee pulp return should avoid excessive application of fresh material and should be integrated with composting treatment, C/N ratio regulation, and balanced nutrient management involving calcium, magnesium, and phosphorus.

5.3. Effects on Soil Enzyme Activity

Changes in soil physicochemical properties further influence biological processes, with enzyme activity serving as a key indicator of soil function. Coffee-pulp return supplies available carbon and nutrient substrates, potentially stimulating the activity of several hydrolases and oxidoreductases [64,65]. Soil enzyme activities provide useful indicators of microbial nutrient transformation, but they should not be interpreted as direct evidence of improved soil function in isolation. For example, increases in β -glucosidase and sucrase may indicate enhanced labile carbon turnover, whereas urease and phosphatase activities reflect potential N and P transformation [66,67]. Nevertheless, enzyme responses should be considered alongside microbial biomass, mineral N, available P, plant nutrient uptake, and yield, because elevated activity may also reflect microbial stress during decomposition of labile or phenolic-rich residues in recently amended soils. Increases in catalase and dehydrogenase generally indicate improved overall microbial oxidative metabolism and soil biological activity [68]. In a specific study, coffee pulp return was reported to increase soil phosphatase and urease activities by 29.84% and 96.00%, respectively [60]; however, a causal link to direct improvements in soil health should not be assumed, as elevated activity may also represent a stress response during high-carbon decomposition. Therefore, enzyme activity data should always be interpreted alongside available nutrients, microbial biomass, and crop uptake indicators to determine whether they translate into effective soil health improvement.

5.4. Effects on Soil Microbial Communities

Coffee pulp mulching exerts significant effects on soil microbial abundance and community structure. Several studies have reported that pulp return increased the abundances of bacteria, fungi, and actinomycetes, as well as bacterial richness and diversity [60,62]. Specifically, coffee pericarp mulching increased bacterial richness and Shannon diversity by 7.75% and 2.79%, respectively. In terms of community composition, the relative abundances of *Proteobacteria* and *Firmicutes* increased, whereas *Cyanobacteria* declined [62,69]. Their relative abundances changed by 22.35%, 80.04%, and −68.38%, respectively, compared with the unmulched control. However, it is important to note that changes in

community composition do not necessarily equate to functional improvement, as different analytical methods (e.g., amplicon sequencing vs. metagenomics) provide different levels of insight. Some organic-amendment studies suggest that pulp return may affect the abundance of functional genes related to nitrogen fixation (*nifH*), organic phosphorus mineralization (*phoD*), and cellulose degradation (*cbhI*), but this conclusion requires further validation from targeted metagenomic and long-term field experiments [70]. In a related coffee-husk composting study, the compost was supplemented after three months with 0.1% (*w/w*) effective microorganisms comprising the N-fixing bacterium *Azotobacter* sp. and the phosphate-solubilizing bacterium *Bacillus megaterium* [71]. In a coffee-husk-derived liquid organic fertilizer, the populations of N-fixing and phosphate-solubilizing bacteria reached 1.37×10^{11} and 1.87×10^{11} CFU mL⁻¹, respectively [72]. This finding provides evidence for the incorporation of specific nutrient-transforming bacteria into coffee-processing-residue compost, although it represents an inoculated coffee-husk system rather than the indigenous microbial response to coffee pulp mulching.

Microbial communities reshaped by pulp return further regulate soil nutrient cycling through multiple pathways. During mineralization, diverse microbial communities rapidly assimilate labile nutrients into microbial biomass, reducing nutrient losses via leaching and surface runoff in high-rainfall regions [73,74]. Nutrients retained in microbial cells are gradually released through repeated cell lysis and re-assimilation, exhibiting a combination of phased concentrated release and long-term slow supply [75,76]. Higher microbial diversity may strengthen trophic interactions between carbon-decomposing and nitrogen-transforming microorganisms [77], mitigating nitrogen immobilization associated with undecomposed organic materials. Consequently, coffee-pulp-type amendments can reshape microbial abundance, diversity, and community composition, but community shifts should not be equated directly with functional improvement. Reported increases in bacterial, fungal, and actinomycete abundance suggest enhanced microbial activity under some conditions, whereas changes in *Proteobacteria*, *Firmicutes*, or *Cyanobacteria* should be interpreted as community restructuring rather than inherently beneficial responses. Functional implications require additional evidence from enzyme assays, mineral N dynamics, plant uptake, and metagenomic or qPCR-based analysis of genes related to nitrogen fixation, phosphorus mineralization, and cellulose degradation.

Furthermore, high microbial diversity endows soil with functional redundancy. During coffee pulp decomposition, polyphenols and caffeine may inhibit sensitive microorganisms, but tolerant functional groups can compensate and sustain nutrient metabolism [78,79]. The activities of key enzymes such as urease, phosphatase, and dehydrogenase can be stabilized or even enhanced. Relevant experimental results have shown that soil urease activity increased by up to 96% following coffee pulp mulching [60].

5.5. Linkages to Plant Growth, Physiology, and Yield

The agronomic significance of the soil changes described above ultimately depends on their transfer to plant growth and production. Reduced bulk density and increased porosity may facilitate root elongation, respiration, and soil exploration, whereas improved nutrient availability and microbial transformation may enhance foliar nutrition, chlorophyll synthesis, stomatal regulation, and photosynthetic carbon assimilation. In immature *Liberica* coffee, the combination of liquid coffee-husk compost (80 mL L⁻¹) and consortium biofertilizer (10 mL L⁻¹) produced the best overall response in plant height, stem diameter, branch traits, leaf area, and chlorophyll index [72]. However, because the amendment was applied together with a biofertilizer, the observed response cannot be attributed solely to the coffee-husk compost.

Improved vegetative growth and photosynthesis may increase assimilate supply for flower-bud differentiation, fruit set, berry expansion, and bean filling. However, direct

evidence for final yield is less consistent than for soil and vegetative responses. Future studies should simultaneously evaluate root biomass and architecture, foliar N, P, and K, chlorophyll and gas-exchange parameters, flowering and fruit-set rates, berry dry-matter accumulation, and harvested yield. Importantly, these downstream responses are not universal: their direction and magnitude depend on amendment characteristics, stabilization degree, application rate, soil texture and acidity, background fertility, rainfall distribution, temperature, and coffee genotype. Detailed effects on plant growth, physiology, and yield formation are discussed further in Section 6.

6. Effects of Coffee Pulp Recycling on Coffee Plant Growth and Physiology and Yield Formation

The soil improvements induced by appropriate coffee-pulp return may be transmitted to plant growth through changes in root development, nutrient uptake, leaf nutrition, and photosynthetic physiology. In addition to belowground and leaf responses, plant height, stem diameter, crown spread, primary branch development, and fruiting-node formation are important indicators linking amendment application to coffee growth and reproductive potential. However, it is crucial to recognize that the overall effect is strongly dose-dependent, with undecomposed or excessive application causing stress that inhibits these very processes.

6.1. Effects on Root Growth and Nutrient Uptake

Coffee-processing-residue amendments may also influence aboveground growth and canopy architecture. In immature *Liberica* coffee, the combined application of liquid coffee-husk compost (80 mL and consortium biofertilizer (10 mL L⁻¹) resulted in the best overall responses in plant height, stem diameter, primary branch number and length, leaf area, and chlorophyll index [72]. Although this combined treatment does not allow the independent effect of coffee pulp to be isolated, it clearly indicates that vegetative growth and branching traits must be taken into account when evaluating the field performance of recycled coffee by-products.

Improved soil physical conditions reduce root penetration resistance, promoting lateral root and root hair development. Low-molecular-weight organic acids produced during decomposition may also enhance the solubility of trace elements like iron and zinc through chelation, improving nutrient acquisition [52,80]. However, the response follows a low-dose stimulation and high-dose inhibition pattern. These responses indicate a bi-phasic pattern, in which moderate application may promote root development whereas excessive or insufficiently decomposed material may inhibit root growth [81,82]. This demonstrates that the root-zone effects of pulp return are not unidirectional but depend on rate and degree of decomposition. At optimal application rates (e.g., a compost ratio of N:P₂O₅:K₂O = 144:144:144 kg·ha⁻¹), increases in soil available nutrients, stem diameter, and crown spread have been observed [36]. During the flowering period, improved soil aeration supports root respiration and the development of lateral roots, while the release of available potassium and micronutrients meets the demand for reproductive organ development [83–87].

During the bean-filling and berry ripening stages, an optimized rhizosphere environment sustains root activity, facilitating the efficient uptake and translocation of N, P, and K, which is critical for photosynthate production and dry matter accumulation [88]. Conversely, applying excessive amounts of coffee pulp or using uncomposted coffee pulp can impose rhizosphere stress, inhibit root growth, disrupt microbial balance, and reduce nutrient uptake, ultimately hindering both flowering and bean filling. In summary, the effect of coffee pulp return on plant nutrient uptake follows a low-dose stimulation and high-

dose inhibition pattern. While it can positively promote nutrient uptake, it can also have an inhibitory effect when applied improperly, demonstrating bidirectional regulation of crop nutrient uptake.

6.2. *Effects on Leaf Nutrition and Photosynthetic Physiology*

The combined application of coffee pulp compost with chemical fertilizers has been shown to improve coffee leaf nutrition and enhance photosynthetic function (Figure 2). In a specific field study, the 0.7FR+O formulation increased leaf N and K status relative to inorganic fertilization alone. Improved N nutrition may support chlorophyll synthesis and Rubisco activity, whereas K contributes to stomatal regulation and osmotic adjustment [52]. The interactive effects of light and nitrogen availability on coffee photosynthetic acclimation have been demonstrated under controlled conditions [89]. However, increases in gas-exchange parameters should be interpreted cautiously because field microclimate differences between mulched and non-mulched plots may partly amplify the observed treatment effects. Concurrently, the leaf nitrogen balance index (NBI) increases, indicating efficient nitrogen assimilation and utilization. Regarding gas exchange, field mulching significantly improved photosynthetic capacity; compared to no mulch, net photosynthetic rate, respiration rate, and water-use efficiency increased by 109.34%, 80.54%, and 104.95%, respectively, in one study [26]. This treatment simultaneously improved the carbon fixation capacity and water use efficiency of the plant, and the photosynthetic output capacity of the coffee tree was significantly enhanced. Photosynthetic parameters were markedly enhanced, attributable in part to more adequate leaf N and K nutrition, improved stomatal dynamics, and stable plant water status. Conversely, it should be noted that microenvironmental differences between the covered-treatment plots and the control plots in the field could inflate the magnitude of the observed improvements across the measured parameters.

The enhanced photosynthetic performance observed following coffee-pulp-type amendment application may be partly associated with improved nutrient availability, leaf chlorophyll status, stomatal regulation, and plant water status [60,90]. This regulatory mechanism operates across the soil–root–shoot–fruit continuum, linking improvements in the rhizosphere environment and nutrient uptake with plant height, stem diameter, canopy and branch development, leaf photosynthesis, fruiting-node formation, and ultimately yield performance [56]. Surface mulching with coffee pulp modulates soil temperature and conserves moisture, sustaining a stable water supply to the root system, which in turn maintains leaf turgor, stomatal function, and CO₂ supply [23,58]. Well-aerated soil also mitigates root hypoxia, preserving root respiration and energy metabolism. At the biochemical level, nitrogen increases Rubisco activity and carbon fixation rates [91,92], while potassium stabilizes chloroplast membranes, regulates light energy transfer, and optimizes stomatal ion transport [93]. Overall, coffee pulp mulching concurrently enhances photosynthetic substrate supply, light energy conversion, and carbon fixation, leading to a significant increase in net photosynthetic rate.

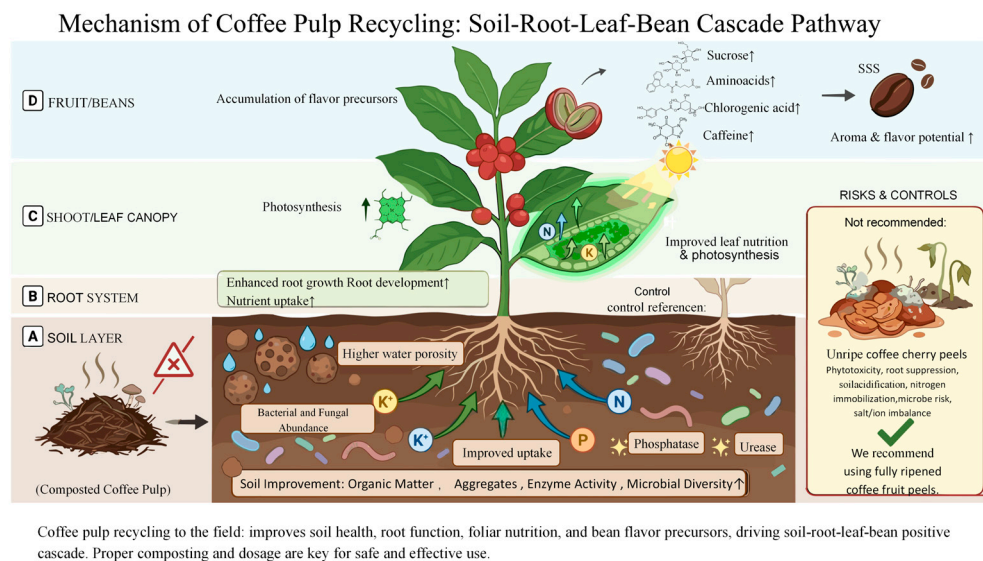


Figure 2. Schematic diagram of the soil–root–leaf–bean continuum in coffee pulp recycling. Proper composting and dosage management convert this continuum into positive cascades, whereas improper use may reverse it toward agronomic risks.

6.3. Effects on Yield Formation

Vegetative architecture provides the structural basis for yield formation because canopy diameter, plagiotropic branch number, bud number, and fruiting-node development determine the potential number of fruit-bearing sites. A field study showed that compost application affected coffee plant height, canopy diameter, plagiotropic branch number, bud number, and yield, with branch and bud development positively associated with productivity [94]. Although this evidence was not specific to coffee-pulp compost, it supports the inclusion of plant architecture as an intermediate link between soil improvement and yield formation.

The slow-release characteristics of composted coffee pulp provide a stable nutrient supply during critical growth stages, including flower bud differentiation, flowering, fruit set, and berry expansion. Flower bud differentiation requires an appropriate C/N ratio and synergistic P/K supply, which compost can help maintain, preventing excessive vegetative growth caused by chemical fertilizers alone. However, excessive application can lead to overly rapid N mineralization, promoting vegetative growth that competes with reproductive development and inhibits flower-bud initiation.

Fruit set depends on adequate K, B, and Zn, which improve pollen viability, fertilization, and hormonal regulation [95]. The decomposition of coffee pulp releases plant-available K and mobilizes soil B and Zn. If this release peak coincides with the flowering stage, fruit set can be enhanced [38]. The period from early fruit enlargement to the grain-filling stage is critical for yield formation. The fruit is the plant's primary reservoir for nutrient competition and has high demands for nitrogen, phosphorus, and potassium [96,97]. During the first two months of ripening, coffee fruit can accumulate up to 43% of its final dry weight and absorb 49% of its final total N, 36% of its P, and 39% of its K [98]. The N and K continuously supplied via mineralization meet these high demands. Potassium, in particular, accumulates in the fruit flesh, playing a key role in sugar transport and osmoregulation, thus influencing fruit enlargement and weight [99]. A specific study in Yunnan, China, found that a combined application (0.7FR+O) increased coffee bean yield by 4.5–6.1% [55]. This yield response may be associated with improved K availability and better synchronization between nutrient supply and crop demand, although direct evidence from temporal nutrient-release measurements remains limited. Adequate K also

optimizes phloem loading and transport, promoting photosynthate distribution to fruits, increasing 100-grain weight, and reducing defects [100,101]. Field trials suggest that applying appropriate amounts of coffee pulp can increase yields by increasing fruiting-node numbers, improving fruit set, and increasing individual fruit weight; however, responses show a clear dose relationship and trade-off between nutrient supply and crop demand under different field conditions in practice. Low-level organic substitution (approximately 30%) can balance both yield and quality, while high-level substitution (>75%) tends to lead to nutrient imbalances and insufficient nutrient supply, resulting in reduced yields. At the same time, excessive yield load can reduce the accumulation of dry matter in individual fruits, leading to a decline in quality. Soil organic matter and nutrient conditions can indirectly affect coffee yield and quality by regulating the plant's photosynthetic physiology.

Returning coffee-pulp-type materials to the field may improve soil physicochemical properties, promote root growth and nutrient uptake, enhance leaf photosynthetic efficiency, and affect berry development and yield formation by modifying source-sink relationships. However, much of the current evidence regarding soil improvement, root uptake, enhanced photosynthesis, and increased yields comes from correlation analyses or single-site trials and still requires further validation through long-term, multi-site, and mechanistic trials.

7. The Effect of Coffee Pulp Recycling on Coffee Quality

The effects of coffee-pulp-type by-product recycling on coffee quality arise from integrated changes in soil conditions, plant physiology, yield formation, and green bean biochemical composition. Coffee-pulp return does not directly produce roasted coffee aroma compounds; rather, it may indirectly influence the precursor pools of sugars, amino acids, chlorogenic acids, caffeine, lipids, and minerals in green beans, thereby modifying the substrate basis for roasting reactions. Improved soil moisture, aeration, and nutrient availability can enhance root uptake, leaf photosynthesis, and assimilate supply to berries, thereby influencing the accumulation of sugars, amino acids, organic acids, and secondary metabolites in green beans. However, these quality responses depend on material type and maturity, application rate, cultivar, environment, fruit maturity, and processing method.

7.1. Effects on the Physical Quality of Green Coffee Beans

Studies have suggested that appropriate coffee pulp return may optimize the physical quality and commercial grade of green coffee beans by improving soil water and nutrient conditions. Reported effects include increased 100-grain weight, enhanced grain plumpness and screening grade, and a reduced proportion of defective beans. Composted pulp provides a sustainable supply of minerals like K, Ca, B, and Zn, which promote the transport and accumulation of photosynthates and help prevent poor seed development. In parallel, the resulting improvement in plant water status, together with K-mediated assimilate transport, may prolong bean filling and increase the allocation of carbohydrates to developing seeds, thereby positively influencing bean size, density, and physical uniformity. Collectively, these mechanisms link soil-level amendments to the physical quality attributes of green coffee beans. Additionally, the moisture-conserving effect of mulch can buffer drought stress during bean expansion, ensuring proper filling and improving grain density [88]. However, this improvement effect has a clear dosage threshold, and the evidence is largely confined to specific studies [55]. However, excessive returning to the field or applying uncomposted pulp will cause nutrient imbalance, plant overgrowth, and increased nutrient competition, which will reduce the quality of green coffee beans and increase the proportion of defective beans. In addition, the quality-enhancing effects of returning coffee pulp to the fields are influenced by ecological factors such as variety,

elevation, and precipitation. The current evaluation system for the physical quality of green coffee beans is relatively traditional and limited in scope. Moving forward, evaluation standards need to be refined by incorporating detailed indicators and objective measurements such as bean density, screen-size distribution, defect classification, color parameters, and sensory evaluation, in order to systematically elucidate the complete mechanism by which returning coffee pulp to the fields improves coffee quality.

7.2. Effects on the Chemical Flavor Precursors in Green Coffee Beans

At the level of green coffee bean chemical composition, 0.7FR+O treatment increased the total sugar content of green coffee beans by 29.5%, chlorogenic acid by 32.0%, caffeine by 14.1%, and overall nutritional quality improved by 8.7–32.0% [43]. These changes may result from the combined effects of improved nutrient acquisition and photosynthetic performance. Enhanced N uptake supports amino acid and protein metabolism, while adequate K promotes stomatal regulation, phloem loading, and the transport of photosynthetic assimilates from leaves to developing berries. Improved soil water availability may further sustain photosynthesis and berry filling during dry periods. The accumulation of sucrose is closely related to improved potassium nutrition [68]. Potassium ions are the core osmotic adjustment ion in the process of phloem loading and unloading, and their supply level directly affects the transport efficiency of photosynthetic assimilates to berries, which in turn determines the final accumulation of soluble sugars such as sucrose in seeds. A moderate increase in chlorogenic acid may improve the functional components and flavor precursor basis of green coffee beans [69]. However, its effect on cupping quality is dual: during the roasting process, chlorogenic acid can break down into acids such as quinic acid, imparting a pleasant acidity to the coffee; however, excessively high levels may also result in excessive astringency and bitterness. Chlorogenic acids account for approximately 6–12% of the green coffee bean dry weight, and their total amount can be reduced by up to 50% during the roasting process, with degradation products contributing to furan and pyrazine formation [87,89]. Therefore, higher levels of these compounds do not guarantee improved cup quality, which also depends on variety, ripeness, processing, and roasting profile. Moreover, the direction and magnitude of these compositional changes may vary among coffee cultivars and environments because genotype, temperature, elevation, rainfall, fruit load, and harvest maturity also regulate primary and secondary metabolism.

7.3. Effects on the Chemistry Behind Coffee Roasting Flavors

The flavor profile of roasted coffee is generated from the thermochemical transformation of green bean precursors during roasting [102]. During roasting, green bean precursors are thermochemically transformed through several partially overlapping pathways: reducing sugars and amino acids participate in the Maillard reaction and Strecker degradation; sugars undergo caramelization; chlorogenic acids and lipids are degraded or oxidized; and multiple components may undergo pyrolysis [103,104]. These reactions generate aroma-active volatile compounds, including furans, pyrazines, pyrroles, aldehydes, and ketones, which collectively contribute to roasted coffee aroma [105,106]. The critical point for this agricultural review is that coffee pulp return can regulate the accumulation of flavor precursors in green beans, thereby modifying the substrate concentration and reaction conditions for these thermal reactions [26,55]. The key point is not to provide a full account of roasting chemistry, but to clarify that field recycling of coffee-pulp-type materials may influence roasted flavor only indirectly by modifying green bean precursor pools. However, fermentation method, drying conditions, storage, and roasting profile can further transform or mask field-induced differences in bean composition. Therefore, changes in green bean precursors should not be interpreted as direct evidence

of predictable changes in final cup aroma. Direct evidence linking specific pulp-return practices to predictable changes in final aroma profiles remains limited and should be treated as a major knowledge gap.

7.4. The Trade-Off Between Yield and Quality

Existing research indicates that co-applying coffee pulp compost can increase flavor precursors in green beans, including free amino acids and total sugars, thereby providing substrates for Maillard and caramelization reactions [55,107]. Amino acids facilitate pyrazine and pyrrole formation, while sugars promote furan-based caramel aromas, with both precursors showing significant correlation with their corresponding aroma compounds [108,109]. A 30% organic substitution rate can slightly improve coffee sweetness and balance, but current evidence cannot confirm that pulp return stably and directionally enhances nutty or cocoa-like characteristics [110]. This uncertainty originates from the inherent trade-off between yield and quality in carbon-nitrogen metabolism, as both share assimilate allocation and compete for primary and secondary metabolic pathways. During berry development, yield formation requires substantial carbon supply for fruit enlargement and seed dry matter accumulation, while flavor precursor synthesis also depends on carbon skeletons [111,112]. Moderate application (e.g., 0.7FR+O) can improve photosynthetic efficiency and boost the overall supply of assimilates, simultaneously supporting fruit filling as well as sucrose and amino acid accumulation, achieving a coordinated improvement in both yield and quality.

Conversely, excessive application of undecomposed pulp can cause a sudden nitrogen surge, stimulating vegetative growth and reducing assimilate transport to fruits. A larger portion of the carbon skeleton may be diverted to nitrogen metabolism, depleting carbohydrate substrates; the resulting decrease in sucrose weakens caramel-like sweetness, while altered amino acid composition disrupts the balance of Maillard reaction products, potentially leading to a yield-quality trade-off characterized by reduced sweetness, weaker aroma complexity, and lower cup balance [113]. Under high fruit load, total leaf number, leaf-to-fruit ratio, and branch growth decrease significantly; dry matter allocated to leaves and branches is negatively correlated with fruit dry matter accumulation, and the proportion of large, healthy beans declines [113]. The accumulation of secondary metabolites also reflects the nutrient-quality balance. Chlorogenic acid synthesis depends on phenylalanine. Moderate potassium supplementation directs carbon flux toward phenylpropanoid metabolism and moderately increases organic acid levels; in contrast, high ammonium nitrogen may inhibit key syntheses, reducing total chlorogenic acid and altering its isomer composition, which affects roasted coffee acidity. Excessive nitrogen supply may also promote caffeine overaccumulation, increase bitterness, and disrupt flavor balance [55].

Overall, the balance between yield and quality is context-dependent. Positive responses are more likely when stabilized materials are applied at appropriate rates in synchrony with crop nutrient demand, whereas excessive or immature application may disrupt source-sink relationships and alter bean biochemical composition. Future studies should therefore jointly evaluate amendment properties, application rate, cultivar, environmental conditions, green bean chemistry, postharvest processing, and sensory quality.

8. Economic and Ecological Benefits of Coffee Pulp Recycling in Agriculture

8.1. Economic Benefits

Coffee-pulp return may generate economic value through input substitution, yield or quality improvement, and reductions in external management costs. As a surface

mulch, it creates a protective layer that reduces soil evaporation and buffers temperature fluctuations, which may reduce irrigation frequency and water demand, particularly in dry or hot valley areas [23]. In addition, the mulch can replace traditional materials such as plastic film or coconut husk, thereby reducing purchase and application costs. As a nutrient management measure, replacing approximately 30% of inorganic fertilizer with decomposed pulp (under specific experimental conditions) has been reported to reduce fertilizer input costs while maintaining stable yield and quality [43]. Furthermore, the strong weed-suppressing effect of the mulch can reduce weed biomass by an estimated 50–80%, significantly decreasing labor requirements for weeding [90]. However, the net benefit differs among direct mulching, composting, liquid-fertilizer production, and bio-char conversion because these pathways require different levels of labor, equipment, energy, and processing time. The high moisture content and low bulk density of fresh pulp may also increase transport and storage costs, particularly when processing facilities are distant from coffee farms. Producer adoption may therefore be limited by technical knowledge, labor availability, access to equipment, and uncertainty regarding suitable application rates. Future studies should include fertilizer savings, labor requirements, transport costs, composting costs, yield response, quality premiums, and farmer adoption constraints in a unified economic assessment.

8.2. Ecological Benefits

At the ecological level, returning coffee pulp to the fields may enhance soil carbon sequestration capacity by increasing organic carbon inputs and promoting the stabilization of carbon within soil aggregates. However, the persistence of this carbon depends on material type, with fresh pulp decomposing more rapidly than compost or biochar. At the same time, compared to open dumping or uncontrolled disposal, returning it to the fields may reduce the risk of high-organic-load leachate being released into water bodies, thereby mitigating non-point source pollution at its source. In terms of soil biology, a number of studies have shown that pulp returning significantly increased the number and diversity of soil microorganisms (bacteria, fungi and actinomycetes were significantly increased), and enhanced the complexity of microbial community structure, thereby improving soil food web stability and ecosystem resilience.

Nevertheless, greenhouse gas outcomes depend on the management method. Poorly aerated compost piles or waterlogged soils may release methane, while rapid nitrogen mineralization following excessive application may increase nitrous oxide emissions. Improper application of fresh pulp may also cause acidic leachate, unpleasant odors, oxygen depletion, temporary nitrogen immobilization, and phytotoxicity associated with caffeine and phenolic compounds. Overall, appropriately stabilized and applied coffee pulp may provide ecological benefits, but these effects remain dependent on material properties, application rate, soil conditions, climate, and management practices. Long-term soil carbon monitoring, greenhouse gas measurements, nutrient-loss assessment, and life-cycle analysis are therefore required.

8.3. Comparison with Alternative Valorization Pathways and Circular-Economy Relevance

Beyond agricultural reuse, coffee pulp and husk can be valorized as animal-feed ingredients after detoxification, substrates for biogas, ethanol, and microbial fermentation, sources of pectin, caffeine, polyphenols, and other bioactive compounds, or raw materials for adsorbents, bioplastics, and other biomaterials. These pathways may generate higher-value products but generally require more standardized raw materials, specialized equipment, energy inputs, technical expertise, and market access.

By contrast, returning stabilized coffee-pulp-type materials to coffee plantations enables local recycling of organic carbon and mineral nutrients, reduces waste-disposal pressure, improves soil fertility, and may lower fertilizer demand. Its relatively low technological requirements and potential for on-site application make it particularly relevant to smallholder production systems. However, agricultural return is not necessarily the most valuable option for all materials. Clean and compositionally consistent fractions may be more suitable for extracting high-value compounds, whereas heterogeneous or nutrient-rich residual fractions may be better suited for composting, biochar production, or soil amendment.

A cascading utilization strategy may therefore provide the greatest overall value: high-value compounds are recovered first, energy or biomaterials are produced where technically and economically feasible, and the remaining nutrient-rich residues are returned to agricultural soils. This integrated approach closes nutrient loops, reduces waste, and is consistent with the principles of the Bio-Circular-Green (BCG) economy and the broader circular economy.

9. Conclusions, Limitations, and Future Directions

9.1. Conclusions

This review concludes that appropriate coffee-pulp return can enhance soil health by increasing organic matter, improving soil structure, and regulating nutrient cycles and microbial communities. These soil-level changes can, in turn, promote root development, leaf photosynthetic performance, and yield formation. However, the effects on green bean chemical composition and final cup quality remain highly variable and are governed by a complex interplay of dose, material maturity, and environmental conditions. The process exhibits pronounced dose-dependence: while moderate application generally yields positive outcomes, excessive application or the use of undecomposed materials can lead to soil acidification, nitrogen immobilization, phenolic allelopathy, and nutrient imbalances.

Notably, while regional and single-year trials suggest that certain substitution rates may enhance yield, nutritional quality, and disease resistance synergistically, these findings require further validation across diverse environments and over longer time scales. For coffee producers, fresh pulp should not be applied directly or at high rates without prior evaluation. The selection of composting, mulching, or fertilizer-substitution strategies should be based on material maturity, nutrient composition, soil fertility, local climate, and available labor and processing capacity.

9.2. Research Limitations and Key Knowledge Gaps

Although returning coffee pulp to soil has demonstrated benefits for yield, quality, and ecological outcomes, several important knowledge gaps remain in current research, limiting mechanistic understanding and large-scale application across diverse coffee production systems under varying environmental conditions globally. Current research is primarily based on short-term experiments, with a significant lack of long-term in situ observations, making it difficult to systematically assess the cumulative effects of coffee pulp return on long-term soil organic carbon accumulation, nutrient dynamics, acidification risk, and microbial community succession. Due to the lack of data support across growing seasons and even multi-year scales, the stability and sustainability of related ecological effects are still uncertain. In addition, the technical parameter system has not been standardized, and there is a lack of a unified conversion framework between the expression methods of application amount ($\text{t}\cdot\text{ha}^{-1}$, $\text{kg}\cdot\text{plant}^{-1}$, and substitution ratio) in different studies. At the same time, the characterization of the degree of coffee pulp decomposition,

moisture content, C/N ratio, and application method is also inconsistent. Important material characteristics, including pH, electrical conductivity, total C, N, P, and K contents, decomposition or maturity degree, and residual concentrations of caffeine, polyphenols, and other potentially phytotoxic compounds, are also frequently underreported. This methodological heterogeneity significantly limits cross-comparisons and meta-analyses of findings from different studies. The evidence chain at the mechanism level is still incomplete. Most of the existing studies are based on single-scale or correlation analysis, and lack systematic comparison across different coffee varieties, ecological zones, and soil types. In particular, the links among pulp inputs, soil-microbiome responses, metabolic changes, and coffee-quality formation remain insufficiently understood across the full production pathway in field conditions to date.

Specifically, the mechanisms linking green bean chemical composition to roasting flavor formation are not well understood. Most studies separately report effects on individual green bean components (e.g., chlorogenic acid, caffeine, sucrose) or on volatile compounds in roasted coffee, but lack a metabolic flow analysis connecting the two. Explanations for improvements in yield and cupping quality have largely remained at the level of indirect correlation, lacking causal evidence supported by stable isotope tracing and multi-omics validation. Finally, integrated evaluation systems remain weak, with few studies incorporating socioeconomic factors such as economic benefits, labor input, farmers' willingness to adopt, and long-term management costs.

9.3. Future Research Directions

To address these gaps, future research should prioritize six interconnected directions: long-term multi-site field trials; standardized pretreatment and maturity evaluation; mechanistic tracing of carbon and nutrient flows; integration of metagenomics, metabolomics, and sensory phenotyping; development of low-cost technologies for smallholders; and establishment of multi-criteria evaluation systems that combine agronomic, environmental, quality, and socioeconomic indicators.

First, long-term fixed-site experiments across diverse ecosystems, altitudes, and soil types are urgently needed to evaluate the cumulative effects of pulp return on soil carbon and nitrogen dynamics, acidification, microbial community succession, and to define regional suitability and ecological safety thresholds. Second, pretreatment processes—including composting, vermicomposting, and carbonization—require standardization to optimize the trade-off between removing inhibitory compounds (e.g., polyphenols and caffeine) and retaining nutrients, thereby mitigating allelopathic risks while improving resource efficiency. Minimum quality criteria should therefore be established before field application, including acceptable ranges for moisture content, pH, C/N ratio, nutrient concentrations, maturity or germination indices, and residual caffeine and polyphenol contents. Third, the mechanistic chain linking soil management to coffee quality must be elucidated by integrating stable isotope tracing (^{13}C , ^{15}N) with multi-omics approaches (metagenomics, metabolomics, and qualityomics) to track the entire pathway from microbial nutrient transformation and plant uptake to the accumulation of flavor precursors in green beans, providing a theoretical basis for targeted flavor regulation. Fourth, low-cost, user-friendly recycling technologies tailored for smallholder farmers should be developed and promoted to streamline processing and field application, thereby enhancing adoption across developing coffee-producing regions. Producers should be encouraged to begin with small field trials, use stabilized materials at locally validated rates, monitor crop and soil responses, and adjust application practices according to soil type, rainfall, coffee cultivar, and crop growth stage. Additionally, screening platforms are needed to study interactions between bioactive compounds in pulp (caffeine, chlorogenic acid) and functional

soil microbes, with the aim of identifying tolerant strains for developing microbial inoculants and composting bio-enhancers. Finally, a comprehensive multi-criteria evaluation system-incorporating polyphenol removal rate, mineralization rate, microbial activity, phytotoxicity indices, and socioeconomic factors-should be established to replace traditional single-parameter assessments and support long-term management decisions.

In addition, a systematic meta-analysis should be conducted to quantitatively synthesize existing global research on coffee pulp recycling. The objective is to account for heterogeneity resulting from differences in climatic conditions, soil properties, pretreatment methods, and field management practices, and to systematically elucidate the unified response patterns of soil physicochemical properties, microbial communities, coffee growth performance, and coffee bean quality indicators to the return of coffee pulp. This analysis can identify key limiting factors affecting the efficiency and ecological benefits of coffee pulp recycling, clarify the optimal application ranges under different environmental conditions, and provide macro-level data support and universal guidance parameters for the standardized promotion and large-scale application of coffee pulp resource utilization technologies worldwide.

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Abbreviations

The following abbreviations are used in this manuscript:

C/N ratio	Carbon-to-Nitrogen ratio
SAK	Soil Available Potassium
SAN	Soil Alkali-hydrolyzable Nitrogen
0.7FR+O	70% of recommended inorganic fertilizer rate + organic amendment
NBI	Nitrogen Balance Index
Rubisco	Ribulose-1,5-bisphosphate carboxylase/oxygenase
NPS	Nitrogen, Phosphorus, Sulfur (fertilizer)
nifH	Nitrogen fixation gene
phoD	Phosphorus mineralization gene
cbhI	Cellulose degradation gene
ATP	Adenosine Triphosphate
DNA	Deoxyribonucleic Acid
PCR	Polymerase Chain Reaction
qPCR	Quantitative Polymerase Chain Reaction

References

1. Bunn, C.; Läderach, P.; Ovalle Rivera, O.; Kirschke, D. A Bitter Cup: Climate Change Profile of Global Production of Arabica and Robusta Coffee. *Clim. Change* **2015**, *129*, 89–101. <https://doi.org/10.1007/s10584-014-1306-x>.
2. Buehren, N.; Goldstein, M.; Molina, E.; Vaillant, J. The Impact of Strengthening Agricultural Extension Services on Women Farmers: Evidence from Ethiopia. *Agric. Econ.* **2019**, *50*, 407–419. <https://doi.org/10.1111/agec.12499>.
3. Siles, P.; Cerdán, C.R.; Staver, C. Smallholder Coffee in the Global Economy—A Framework to Explore Transformation Alternatives of Traditional Agroforestry for Greater Economic, Ecological, and Livelihood Viability. *Front. Sustain. Food Syst.* **2022**, *6*, 808207. <https://doi.org/10.3389/fsufs.2022.808207>.
4. Hu, S.; Gil-Ramírez, A.; Martín-Trueba, M.; Benítez, V.; Aguilera, Y.; Martín-Cabrejas, M.A. Valorization of Coffee Pulp as Bioactive Food Ingredient by Sustainable Extraction Methodologies. *Curr. Res. Food Sci.* **2023**, *6*, 100475. <https://doi.org/10.1016/j.crfs.2023.100475>.
5. Blumenthal, P.; Steger, M.C.; Quintanilla Bellucci, A.; Segatz, V.; Rieke-Zapp, J.; Sommerfeld, K.; Schwarz, S.; Einfalt, D.; Lachenmeier, D.W. Production of Coffee Cherry Spirits from *Coffea arabica* Varieties. *Foods* **2022**, *11*, 1672. <https://doi.org/10.3390/foods11121672>.
6. Tamilselvan, K.; Sundarajan, S.; Ramakrishna, S.; Amirul, A.-A.A.; Vigneswari, S. Sustainable Valorisation of Coffee Husk into Value Added Product in the Context of Circular Bioeconomy: Exploring Potential Biomass-Based Value Webs. *Food Bioprod. Process.* **2024**, *145*, 187–202. <https://doi.org/10.1016/j.fbp.2024.03.008>.
7. Janissen, B.; Huynh, T. Chemical Composition and Value-Adding Applications of Coffee Industry by-Products: A Review. *Resour. Conserv. Recycl.* **2018**, *128*, 110–117. <https://doi.org/10.1016/j.resconrec.2017.10.001>.
8. Getachew, M.T.; Hiruy, A.M.; Mazharuddin, M.M.; Mamo, T.T.; Feseha, T.A.; Mekonnen, Y.S. Effect of Chemical and Biological Additives on Production of Biogas from Coffee Pulp Silage. *Sci. Rep.* **2023**, *13*, 12199. <https://doi.org/10.1038/s41598-023-39163-w>.
9. Cangussu, L.B.; Melo, J.C.; Franca, A.S.; Oliveira, L.S. Chemical Characterization of Coffee Husks, a by-Product of *Coffea arabica* Production. *Foods* **2021**, *10*, 3125. <https://doi.org/10.3390/foods10123125>.
10. Dadi, D.; Daba, G.; Beyene, A.; Luis, P.; Van der Bruggen, B. Composting and Co-Composting of Coffee Husk and Pulp with Source-Separated Municipal Solid Waste: A Breakthrough in Valorization of Coffee Waste. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 263–277. <https://doi.org/10.1007/s40093-019-0256-8>.
11. Ruiz, M.; Reiser, M.; Hafner, G.; Kranert, M. A Study about Methane Emissions from Different Composting Systems for Coffee By-Products on Costa Rica. *Environ. Ecol. Res.* **2018**, *6*, 461–470. <https://doi.org/10.13189/eer.2018.060506>.
12. Hoseini, M.; Cocco, S.; Casucci, C.; Cardelli, V.; Corti, G. Coffee By-Products Derived Resources. A Review. *Biomass Bioenergy* **2021**, *148*, 106009. <https://doi.org/10.1016/j.biombioe.2021.106009>.
13. Alemayehu, Y.A.; Asfaw, S.L.; Terfie, T.A. Hydrolyzed Urine as a Nutrient and Condition Corrector for Enhanced Coffee Pulp Composting. *Environ. Technol. Innov.* **2022**, *28*, 102703. <https://doi.org/10.1016/j.eti.2022.102703>.
14. Rosolem, C.A.; Almeida, D.S.; Cruz, C.V. Polyol-Ester Impact on Boron Foliar Absorption and Remobilization in Cotton and Coffee Trees. *Rev. Bras. DE Ciênc. DO Solo* **2020**, *44*, e0200023. <https://doi.org/10.36783/18069657rbcs20200023>.
15. Salamanca-Jimenez, A.; Doane, T.A.; Horwath, W.R. Coffee Response to Nitrogen and Soil Water Content during the Early Growth Stage. *J. Plant Nutr. Soil Sci.* **2017**, *180*, 614–623. <https://doi.org/10.1002/jpln.201600601>.
16. Pyrzynska, K. Useful Extracts from Coffee By-Products: A Brief Review. *Separations* **2024**, *11*, 334. <https://doi.org/10.3390/separations11120334>.
17. Chali, G.; Wakgari, T. Effect of Integrated Use of Coffee Husk Compost and NPS Fertilizer on Soil Physicochemical Properties and Yield of Coffee (*Coffea arabica* L.) at Haru, Ethiopia. *Agric. For. Fish.* **2021**, *10*, 233–244. <https://doi.org/10.11648/j.aff.20211006.14>.
18. Figueroa-Varela, P.A.; Duque-Dussán, E. Functional Characterization of Native Microorganisms from the Pulp of *Coffea arabica* L. Var. Castillo and Cenicafé 1 for Postharvest Applications and Compost Enhancement. *Appl. Microbiol.* **2025**, *5*, 86. <https://doi.org/10.3390/applmicrobiol5030086>.
19. Zoca, S.M.; Penn, C.J.; Rosolem, C.A.; Alves, A.R.; Neto, L.O.; Martins, M.M. Coffee Processing Residues as a Soil Potassium Amendment. *Int. J. Recycl. Org. Waste Agric.* **2014**, *3*, 155–165. <https://doi.org/10.1007/s40093-014-0078-7>.
20. Baumert, V.L.; Vasilyeva, N.A.; Vladimirov, A.A.; Meier, I.C.; Kögel-Knabner, I.; Mueller, C.W. Root Exudates Induce Soil Macroaggregation Facilitated by Fungi in Subsoil. *Front. Environ. Sci.* **2018**, *6*, 140. <https://doi.org/10.3389/fenvs.2018.00140>.

21. Getachew, M.; Tolassa, K.; De Frenne, P.; Verheyen, K.; Tack, A.J.M.; Hylander, K.; Ayalew, B.; Boeckx, P. The Relationship between Elevation, Soil Temperatures, Soil Chemical Characteristics, and Green Coffee Bean Quality and Biochemistry in South-west Ethiopia. *Agron. Sustain. Dev.* **2022**, *42*, 61. <https://doi.org/10.1007/s13593-022-00801-8>.
22. Bi, X.; Yu, H.; Hu, F.; Fu, X.; Li, Y.; Li, Y.; Yang, Y.; Liu, D.; Li, G.; Shi, R.; et al. A Systematic Analysis of the Correlation between Flavor Active Differential Metabolites and Multiple Bean Ripening Stages of *Coffea arabica* L. *Molecules* **2024**, *29*, 180. <https://doi.org/10.3390/molecules29010180>.
23. Zhang, A.; Chen, S.-S.; Lin, X.-J.; Yan, L.; Huang, Y.-L.; Sun, Y.; Zhao, Q.-Y.; Zhao, S.-G.; Li, L.-H.; Long, Y.-Z.; et al. Effects of Cascara Cherry and Other Coffee Litter Mulching on Soil Properties, Photosynthesis, and Water Use Efficiency of *Coffea canephora* Pierre Ex a. Froehner Cv. Reyan No.1 Seedling. *Agronomy* **2024**, *14*, 1418. <https://doi.org/10.3390/agronomy14071418>.
24. Cao, X.; Wu, H.; Viejo, C.G.; Dunshea, F.R.; Suleria, H.A.R. Effects of Postharvest Processing on Aroma Formation in Roasted Coffee—A Review. *Int. J. Food Sci. Technol.* **2023**, *58*, 1007–1027. <https://doi.org/10.1111/ijfs.16261>.
25. Münchow, M.; Alstrup, J.; Steen, I.; Giacalone, D. Roasting Conditions and Coffee Flavor: A Multi-Study Empirical Investigation. *Beverages* **2020**, *6*, 29. <https://doi.org/10.3390/beverages6020029>.
26. Bastian, F.; Hutabarat, O.S.; Dirpan, A.; Nainu, F.; Harapan, H.; Emran, T.B.; Simal-Gandara, J. From Plantation to Cup: Changes in Bioactive Compounds during Coffee Processing. *Foods* **2021**, *10*, 2827. <https://doi.org/10.3390/foods10112827>.
27. Bonilla, J.; Gordillo, G.; Cantor, C. Experimental Gasification of Coffee Husk Using Pure Oxygen-Steam Blends. *Front. Energy Res.* **2019**, *7*, 127. <https://doi.org/10.3389/fenrg.2019.00127>.
28. Setiawan, A.; Zakarya, M.; Alchalil, A.; Nur, T. Experimental Investigation and Simulation of Slow Pyrolysis Process of Arabica Coffee Agroindustry Residues in a Pilot-Scale Reactor. *J. Ecol. Eng.* **2022**, *23*, 259–268. <https://doi.org/10.12911/22998993/150693>.
29. Duque-Dussán, E.; Bappah, M.; Sanz-Urbe, J.R.; Nainggolan, E.A. Thermo-Chemical Characterization of Coffee Husk from a New Variety (*Coffea arabica* L. Var. Cenicafé 1) for Biofuel Production. *Sci. Agric. Bohem.* **2025**, *1*, 1–22. <https://doi.org/10.7160/sab.2025.560101>.
30. dos Santos, É.M.; de Macedo, L.M.; Ataíde, J.A.; Delafiori, J.; de Oliveira Guarnieri, J.P.; Rosa, P.C.P.; Ruiz, A.L.T.G.; Lancellotti, M.; Jozala, A.F.; Catharino, R.R.; et al. Antioxidant, Antimicrobial and Healing Properties of an Extract from Coffee Pulp for the Development of a Phytocosmetic. *Sci. Rep.* **2024**, *14*, 4453. <https://doi.org/10.1038/s41598-024-54797-0>.
31. Murthy, P.S.; Madhava Naidu, M. Sustainable Management of Coffee Industry By-Products and Value Addition—A Review. *Resour. Conserv. Recycl.* **2012**, *66*, 45–58. <https://doi.org/10.1016/j.resconrec.2012.06.005>.
32. Andrews, E.M.; Kassama, S.; Smith, E.E.; Brown, P.H.; Khalsa, S.D.S. A Review of Potassium-Rich Crop Residues Used as Organic Matter Amendments in Tree Crop Agroecosystems. *Agriculture* **2021**, *11*, 580. <https://doi.org/10.3390/agriculture11070580>.
33. Takala, B. Dry Matter Yield and Nutrient Uptakes of Arabica Coffee Seedlings as Influenced by Lime and Coffee Husk Compost Amendments at Western Ethiopia. *Pelita Perkeb. (A Coffee Cocoa Res. J.)* **2021**, *37*, 97–106. <https://doi.org/10.22302/icri.jur.pelita-perkebunan.v37i2.468>.
34. Mawazo, J.S.; Jerome, P.M. Composting Coffee Pulp with Minjingu Phosphate Rock Improves Phosphorus Availability for Tomato Uptake. *Afr. J. Agric. Res.* **2019**, *14*, 1051–1057. <https://doi.org/10.5897/AJAR2018.13089>.
35. El-Beltagi, H.S.; Basit, A.; Mohamed, H.I.; Ali, I.; Ullah, S.; Kamel, E.A.R.; Shalaby, T.A.; Ramadan, K.M.A.; Alkhateeb, A.A.; Ghazzawy, H.S. Mulching as a Sustainable Water and Soil Saving Practice in Agriculture: A Review. *Agronomy* **2022**, *12*, 1881. <https://doi.org/10.3390/agronomy12081881>.
36. Jiang, Z.; Liu, X.; Sun, W.; Cui, N.; Guo, J.; Chen, H.; Huang, W. Fertilizer Optimization Combined with Coffee Husk Returning to Improve Soil Environmental Quality and Young Coffee Tree Growth. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 650–665. <https://doi.org/10.1007/s42729-023-01572-1>.
37. Mussatto, S.I.; Machado, E.M.S.; Martins, S.; Teixeira, J.A. Production, Composition, and Application of Coffee and Its Industrial Residues. *Food Bioprocess Technol.* **2011**, *4*, 661–672. <https://doi.org/10.1007/s11947-011-0565-z>.
38. Dong, Y.; Zhao, Q.; Zhang, A.; Zhao, S.; Long, Y.; Sun, Y.; Tan, J.; Lin, X. Effects of Application of Acid Soil Conditioner and Fermented Coffee Peels on Growth of Coffee Seedlings and Fertility and Enzyme Activities of Soil. *Fujian J. Agric. Sci.* **2022**, *37*, 1493–1502. <https://doi.org/10.19303/j.issn.1008-0384.2022.011.016>.
39. Tang, M.; Liu, R.; Li, H.; Gao, X.; Wu, P.; Zhang, C. Optimizing Soil Moisture Conservation and Temperature Regulation in Rainfed Jujube Orchards of China's Loess Hilly Areas Using Straw and Branch Mulching. *Agronomy* **2023**, *13*, 2121. <https://doi.org/10.3390/agronomy13082121>.
40. Prosdociimi, M.; Tarolli, P.; Cerdà, A. Mulching Practices for Reducing Soil Water Erosion: A Review. *Earth-Sci. Rev.* **2016**, *161*, 191–203. <https://doi.org/10.1016/j.earscirev.2016.08.006>.

41. Pandey, A.; Soccol, C.R.; Nigam, P.; Brand, D.; Mohan, R.; Roussos, S. Biotechnological Potential of Coffee Pulp and Coffee Husk for Bioprocesses. *Biochem. Eng. J.* **2000**, *6*, 153–162. [https://doi.org/10.1016/S1369-703X\(00\)00084-X](https://doi.org/10.1016/S1369-703X(00)00084-X).
42. Liu, J.; Cui, W.; Qi, Z.; Wu, L.; Zhou, W. Plant-Derived Waste as a Component of Growing Media: Manifestations, Assessments, and Sources of Their Phytotoxicity. *Plants* **2024**, *13*, 2000. <https://doi.org/10.3390/plants13142000>.
43. Mantovani, J.R.; Paula, D.W.D.; Rezende, T.T.; Silva, A.B.D.; Andrade, P.C.C.; Landgraf, P.R.C. Early Growth of Coffee Plants and Soil Fertility Properties in Response to Coffee Husk Application. *Coffee Sci.* **2018**, *13*, 356. <https://doi.org/10.25186/cs.v13i3.1466>.
44. Kasongo, R.K.; Verdoodt, A.; Kanyankagote, P.; Baert, G.; Ranst, E.V. Coffee Waste as an Alternative Fertilizer with Soil Improving Properties for Sandy Soils in Humid Tropical Environments. *Soil Use Manag.* **2011**, *27*, 94–102. <https://doi.org/10.1111/j.1475-2743.2010.00315.x>.
45. Chaves, B.; Redin, M.; Giacomini, S.J.; Schmatz, R.; Léonard, J.; Ferchaud, F.; Recous, S. The Combination of Residue Quality, Residue Placement and Soil Mineral N Content Drives C and N Dynamics by Modifying N Availability to Microbial Decomposers. *Soil Biol. Biochem.* **2021**, *163*, 108434. <https://doi.org/10.1016/j.soilbio.2021.108434>.
46. Shea, E.; Wang, Z.; Allison, B.; Simmons, C. Alleviating Phytotoxicity of Soils Biosolarized with Almond Processing Residues. *Environ. Technol. Innov.* **2021**, *23*, 101662. <https://doi.org/10.1016/j.eti.2021.101662>.
47. Ashenae, F.S.; Tuji, F.A. Determining the Maturity of Co-Composted Coffee Husks Using Microbial and Chemical Indicators. *Afr. J. Microbiol. Res.* **2026**, *20*, 79–90. <https://doi.org/10.5897/AJMR2025.9834>.
48. Frómeta, R.A.R.; Sánchez, J.L.; García, J.M.R. Evaluation of Coffee Pulp as Substrate for Polygalacturonase Production in Solid State Fermentation. *Emir. J. Food Agric.* **2020**, *32*, 117–124. <https://doi.org/10.9755/ejfa.2020.v32.i2.2068>.
49. Guo, R.; Li, G.; Jiang, T.; Schuchardt, F.; Chen, T.; Zhao, Y.; Shen, Y. Effect of Aeration Rate, C/N Ratio and Moisture Content on the Stability and Maturity of Compost. *Bioresour. Technol.* **2012**, *112*, 171–178. <https://doi.org/10.1016/j.biortech.2012.02.099>.
50. Nada, W.M. Stability and Maturity of Maize Stalks Compost as Affected by Aeration Rate, C/N Ratio and Moisture Content. *J. Soil Sci. Plant Nutr.* **2015**, *15*, 751–764. <https://doi.org/10.4067/S0718-95162015005000051>.
51. Bonanomi, G.; Incerti, G.; Barile, E.; Capodilupo, M.; Antignani, V.; Mingo, A.; Lanzotti, V.; Scala, F.; Mazzoleni, S. Phytotoxicity, Not Nitrogen Immobilization, Explains Plant Litter Inhibitory Effects: Evidence from Solid-State ¹³C NMR Spectroscopy. *New Phytol.* **2011**, *191*, 1018–1030. <https://doi.org/10.1111/j.1469-8137.2011.03765.x>.
52. Shemekite, F.; Gómez-Brandón, M.; Franke-Whittle, I.H.; Praehauser, B.; Insam, H.; Assefa, F. Coffee Husk Composting: An Investigation of the Process Using Molecular and Non-Molecular Tools. *Waste Manag.* **2014**, *34*, 642–652. <https://doi.org/10.1016/j.wasman.2013.11.010>.
53. Zhou, W.; Liao, J.; Zhou, B.; Yang, R.; Lin, W.; Zhang, D.; Wang, H.; Qi, Z. Rapidly Reducing Phytotoxicity of Green Waste for Growing Media by Incubation with Ammonium. *Environ. Technol. Innov.* **2023**, *31*, 103136. <https://doi.org/10.1016/j.eti.2023.103136>.
54. Brunetti, G.; Traversa, A.; De Mastro, F.; Coccozza, C. Short Term Effects of Synergistic Inorganic and Organic Fertilization on Soil Properties and Yield and Quality of Plum Tomato. *Sci. Hortic.* **2019**, *252*, 342–347. <https://doi.org/10.1016/j.scienta.2019.04.002>.
55. Huang, W.; Liu, X.; Li, R.; Wang, Y.; Dong, J.; Wang, X.; Cui, N.; Chen, Z. Enhancing Soil Microenvironment, Bean Yield, Nutritional Quality and Flavor of *Coffea arabica* through Synergistic Inorganic-Organic Fertilization in Southwest China. *Ind. Crops Prod.* **2025**, *234*, 121526. <https://doi.org/10.1016/j.indcrop.2025.121526>.
56. Cervera-Mata, A.; Molinero-García, A.; Martín-García, J.M.; Delgado, G. Sequential Effects of Spent Coffee Grounds on Soil Physical Properties. *Soil Use Manag.* **2023**, *39*, 286–297. <https://doi.org/10.1111/sum.12853>.
57. Cervera-Mata, A.; Martín-García, J.M.; Delgado, R.; Sánchez-Marañón, M.; Delgado, G. Short-Term Effects of Spent Coffee Grounds on the Physical Properties of Two Mediterranean Agricultural Soils. *Int. Agrophysics* **2019**, *33*, 205–216. <https://doi.org/10.31545/intagr/109412>.
58. Sánchez-Reinoso, A.D.; Ávila-Pedraza, E.Á.; Lombardini, L.; Restrepo-Díaz, H. The Application of Coffee Pulp Biochar Improves the Physical, Chemical, and Biological Characteristics of Soil for Coffee Cultivation. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 2512–2524. <https://doi.org/10.1007/s42729-023-01208-4>.
59. Jiang, W.; Li, T.; Ma, J.; Wang, X.; Cheng, Y.; Gong, L.; Zhang, J.; Chen, G. Organic Materials Input Promotes the Soil Aggregate Sequestration through Changing Soil Aggregates Structure and Stability. *J. Environ. Manag.* **2025**, *393*, 127027. <https://doi.org/10.1016/j.jenvman.2025.127027>.

60. Jiang, Z.; Lou, Y.; Liu, X.; Sun, W.; Wang, H.; Liang, J.; Guo, J.; Li, N.; Yang, Q. Combined Application of Coffee Husk Compost and Inorganic Fertilizer to Improve the Soil Ecological Environment and Photosynthetic Characteristics of Arabica Coffee. *Agronomy* **2023**, *13*, 1212. <https://doi.org/10.3390/agronomy13051212>.
61. Wu, C.; Jiang, N.; Zhang, Y.; Jiang, D.; Wang, S.; Hu, J.; Chen, Z.; Chen, L. Mechanistic Links between Phosphorus Activators and Organic Phosphorus Mineralization: Phosphatase-Mediated Responses in Soils with Contrasting Microbial Activity. *Appl. Soil Ecol.* **2026**, *217*, 106654. <https://doi.org/10.1016/j.apsoil.2025.106654>.
62. Zhao, S.; Zhang, A.; Zhao, Q.; Zhang, Y.; Wang, D.; Su, L.; Lin, X.; Sun, Y.; Yan, L.; Wang, X.; et al. Effects of Coffee Pericarp and Litter Mulching on Soil Microbiomes Diversity and Functions in a Tropical Coffee Plantation, South China. *Front. Microbiol.* **2024**, *14*, 1323902. <https://doi.org/10.3389/fmicb.2023.1323902>.
63. Cui, J.; Zhu, R.; Wang, X.; Xu, X.; Ai, C.; He, P.; Liang, G.; Zhou, W.; Zhu, P. Effect of High Soil C/N Ratio and Nitrogen Limitation Caused by the Long-Term Combined Organic-Inorganic Fertilization on the Soil Microbial Community Structure and Its Dominated SOC Decomposition. *J. Environ. Manag.* **2022**, *303*, 114155. <https://doi.org/10.1016/j.jenvman.2021.114155>.
64. Tan, Y.T.; Chua, A.S.M.; Ngoh, G.C. Deep Eutectic Solvent for Lignocellulosic Biomass Fractionation and the Subsequent Conversion to Bio-Based Products—A Review. *Bioresour. Technol.* **2020**, *297*, 122522. <https://doi.org/10.1016/j.biortech.2019.122522>.
65. Wasilkowski, D.; Nowak, A.; Plaza, G.; Mroziak, A. Effects of Pulp and Na-Bentonite Amendments on the Mobility of Trace Elements, Soil Enzymes Activity and Microbial Parameters under Ex Situ Aided Phytostabilization. *PLoS ONE* **2017**, *12*, e0169688. <https://doi.org/10.1371/journal.pone.0169688>.
66. Bulmer, G.S.; de Andrade, P.; Field, R.A.; van Munster, J.M. Recent Advances in Enzymatic Synthesis of β -Glucan and Cellulose. *Carbohydr. Res.* **2021**, *508*, 108411. <https://doi.org/10.1016/j.carres.2021.108411>.
67. Li, C.; Ma, X.; Wang, Y.; Sun, Q.; Chen, M.; Zhang, C.; Ding, S.; Dai, Z. Root-Mediated Acidification, Phosphatase Activity and the Phosphorus-Cycling Microbial Community Enhance Phosphorus Mobilization in the Rhizosphere of Wetland Plants. *Water Res.* **2024**, *255*, 121548. <https://doi.org/10.1016/j.watres.2024.121548>.
68. Taggart, M.G.; Baah, D.S.; Allen, S.; Khan, Z.; Arnscheidt, J.; Jordan, P.; O'Hagan, B.M.G.; Ibrahim, A.D.; Rao, J.R.; Ternan, N.G. Fitting Soil Extracellular Enzyme Activity into the Complex Network of Abiotic and Biotic Soil Properties Often Associated with Soil Health. *Front. Microbiol.* **2025**, *16*, 1638267. <https://doi.org/10.3389/fmicb.2025.1638267>.
69. Herlihy, M. Distribution of Nitrifying and Heterotrophic Microorganisms in Cutover Peats. *Soil Biol. Biochem.* **1973**, *5*, 621–628. [https://doi.org/10.1016/0038-0717\(73\)90052-7](https://doi.org/10.1016/0038-0717(73)90052-7).
70. da Silva, C.C.G.; Medeiros, E.V. de; Fracetto, G.G.M.; Fracetto, F.J.C.; Martins Filho, A.P.; Lima, J.R. de S.; Duda, G.P.; Costa, D.P. da; Lira Junior, M.A.; Hammecker, C. Coffee Waste as an Eco-Friendly and Low-Cost Alternative for Biochar Production Impacts on Sandy Soil Chemical Attributes and Microbial Gene Abundance. *Bragantia* **2021**, *80*, e2121. <https://doi.org/10.1590/1678-4499.20200459>.
71. Dzung, N.A.; Dzung, T.T.; Khanh, V.T.P. Evaluation of Coffee Husk Compost for Improving Soil Fertility and Sustainable Coffee Production in Rural Central Highland of Vietnam. *Resour. Environ.* **2013**, *3*, 77–82.
72. Maxiselly, Y.; Nafy, F.R.; Anjarsari, I.R.D. Morphological Trait Variation of the Immature Liberica Coffee (*Coffea liberica*) from West Java Applied Difference of Coffee Husk Compost and Biofertilizer. *Biodiversitas J. Biol. Divers.* **2023**, *24*. <https://doi.org/10.13057/biodiv/d241118>.
73. Karmakar, K.; Roy, D.; Pal, S.; Chowdhury, B.; Choudhury, A. EPS-Producing Bacteria Promote Aggregation in Soil Preventing the Leaching Loss of Nutrient. *Curr. Microbiol.* **2025**, *82*, 307. <https://doi.org/10.1007/s00284-025-04295-x>.
74. Wichern, F.; Schlösser, C.; Meisen, S.A.; Hemkemeyer, M. Cover Crop Nitrogen Uptake: Summer Drought Constraints and Mild Winter Recovery. *Nutr. Cycl. Agroecosystems* **2026**, *132*, 46. <https://doi.org/10.1007/s10705-026-10496-y>.
75. Peng, X.; Gao, S.; Ma, S.; Liao, H.; Liu, Y.-R.; Chen, W.; Huang, Q.; Hao, X. Repeated Labile Carbon Inputs Trigger Soil Microbial Necromass Decomposition through Increasing Microbial Diversity and Hierarchical Interactions. *Soil Biol. Biochem.* **2024**, *191*, 109344. <https://doi.org/10.1016/j.soilbio.2024.109344>.
76. Maillard, F.; Michaud, T.J.; See, C.R.; DeLancey, L.C.; Blazewicz, S.J.; Kimbrel, J.A.; Pett-Ridge, J.; Kennedy, P.G. Melanization Slows the Rapid Movement of Fungal Necromass Carbon and Nitrogen into Both Bacterial and Fungal Decomposer Communities and Soils. *mSystems* **2023**, *8*, e00390-23. <https://doi.org/10.1128/msystems.00390-23>.
77. Li, W.; Zhao, J.; Feng, T.; Zhang, X.; Li, Z.; Zheng, W.; Zhai, B. Bacterial–Fungal Interkingdom Interactions Mediate Effects of Biodiversity on Soil Carbon Dynamics in Wheat Fields under Long-Term Fertilization. *Appl. Soil Ecol.* **2025**, *211*, 106167. <https://doi.org/10.1016/j.apsoil.2025.106167>.
78. Maia, S.; Ferreira, H.; Oliveira, M.B.P.P.; Alves, R.C. Coffee By-Products: An Overview of Their Antimicrobial Properties. *Molecules* **2026**, *31*, 1768. <https://doi.org/10.3390/molecules31101768>.

79. Khochapong, W.; Ketnawa, S.; Ogawa, Y.; Punbusayakul, N. Effect of in Vitro Digestion on Bioactive Compounds, Antioxidant and Antimicrobial Activities of Coffee (*Coffea arabica* L.) Pulp Aqueous Extract. *Food Chem.* **2021**, *348*, 129094. <https://doi.org/10.1016/j.foodchem.2021.129094>.
80. Karimi, M.; Ahmadi, N.; Ebrahimi, M. Corrigendum to “Photoreceptor Regulation of *Hypericum perforatum* L. (Cv. Topas) Flowering under Different Light Spectrums in the Controlled Environment System” [Environ. Exp. Bot. 196 (2022) 104797]. *Environ. Exp. Bot.* **2022**, *201*, 104987. <https://doi.org/10.1016/j.envexpbot.2022.104987>.
81. Lhokitasari, R.F.; Hayati, M.; Rahmawati, M. Growth and Production of Potato Mini Tubers (*Solanum tuberosum* L.) in the Aeroponic System by Root Zone Treatment and Concentration of Leaf-Fertilizer. *IOP Conf. IOP Conf. Ser. Earth Environ. Sci.* **2022**, *951*, 012037. <https://doi.org/10.1088/1755-1315/951/1/012037>.
82. Zhang, X.; Khalid, M.; Wang, R.; Chi, Y.; Zhang, D.; Chu, S.; Yang, X.; Zhou, P. Enhancing Lettuce Growth and Rhizosphere Microbial Community with *Bacillus safensis* YM1 Compost in Soilless Cultivation: An Agricultural Approach for Kitchen Waste Utilization. *Sci. Hortic.* **2023**, *321*, 112345. <https://doi.org/10.1016/j.scienta.2023.112345>.
83. Jin, C.; Lei, H.; Chen, J.; Xiao, Z.; Leghari, S.J.; Yuan, T.; Pan, H. Effect of Soil Aeration and Root Morphology on Yield under Aerated Irrigation. *Agronomy* **2023**, *13*, 369. <https://doi.org/10.3390/agronomy13020369>.
84. Wendel, A.S.; Bauke, S.L.; Ieperuma, J.C.; Funken, K.; Frindte, K.; Knief, C. Implications of Reduced Root-Soil Contact for Microbial Rhizosphere Establishment and Early Plant Growth Performance. *Soil Biol. Biochem.* **2025**, *207*, 109816. <https://doi.org/10.1016/j.soilbio.2025.109816>.
85. Wang, D.; He, X.; Baer, M.; Lami, K.; Yu, B.; Tassinari, A.; Salvi, S.; Schaaf, G.; Hochholdinger, F.; Yu, P. Lateral Root Enriched Massilia Associated with Plant Flowering in Maize. *Microbiome* **2024**, *12*, 124. <https://doi.org/10.1186/s40168-024-01839-4>.
86. Ma, X.; Li, H.; Xu, Y.; Liu, C. Effects of Organic Fertilizers via Quick Artificial Decomposition on Crop Growth. *Sci. Rep.* **2021**, *11*, 3900. <https://doi.org/10.1038/s41598-021-83576-4>.
87. Bader, B.R.; Taban, S.K.; Fahmi, A.H.; Abood, M.A.; Hamdi, G.J. Potassium Availability in Soil Amended with Organic Matter and Phosphorous Fertiliser under Water Stress during Maize (*Zea mays* L) Growth. *J. Saudi Soc. Agric. Sci.* **2021**, *20*, 390–394. <https://doi.org/10.1016/j.jssas.2021.04.006>.
88. Salvador, H.P.; Vieira, H.D.; Gontijo, I.; Marques, I.; Ramalho, J.C.; Partelli, F.L. Nutrient Dynamics in the Berry, Bean, and Husk of Six *Coffea canephora* Genotypes throughout Fruit Maturation. *Sci. Rep.* **2025**, *15*, 27570. <https://doi.org/10.1038/s41598-025-13171-4>.
89. Godoy, A.G.; Avila, R.T.; da Silva, M.M.; Ramalho, J.D.C.; Martins, S.C.V.; DaMatta, F.M. Growth and Photosynthetic Acclimation of Coffee Plants under Contrasting Irradiance and Nitrogen Supplies. *Plant Physiol Biochem.* **2025**, *228*, 110212. <https://doi.org/10.1016/j.plaphy.2025.110212>.
90. Yunita, D.M.; Hanuf, A.A.; Lutfi, M.W.; Soemarno. Effects of Biopore Infiltration Holes with Compost (BIHC) on Total Soil Nitrogen in Coffee Plantation. *Agriverse* **2025**, *1*, 44–52. <https://doi.org/10.33005/agriverse.v1i1.6>.
91. Chai, H.; Gao, L.; Zhao, C.; Liu, X.; Jiang, D.; Dai, T.; Tian, Z. Low Nitrogen Priming Enhances Rubisco Activation and Allocation of Nitrogen to the Photosynthetic Apparatus as an Adaptation to Nitrogen-Deficit Stress in Wheat Seedling. *J. Plant Physiol.* **2024**, *303*, 154337. <https://doi.org/10.1016/j.jplph.2024.154337>.
92. Li, Y.-T.; Li, Y.; Li, Y.-N.; Liang, Y.; Sun, Q.; Li, G.; Liu, P.; Zhang, Z.-S.; Gao, H.-Y. Dynamic Light Caused Less Photosynthetic Suppression, Rather than More, under Nitrogen Deficit Conditions than under Sufficient Nitrogen Supply Conditions in Soybean. *BMC Plant Biol.* **2020**, *20*, 339. <https://doi.org/10.1186/s12870-020-02516-y>.
93. Wu, L.; Luo, Q.; Zhu, T.; Wei, Y. Potassium Deficiency Impairs Photosynthetic Induction via Disrupted Electron Transport and Photochemistry in *Phaseolus Vulgaris*. *Front. Plant Sci.* **2026**, *17*, 1722785. <https://doi.org/10.3389/fpls.2026.1722785>.
94. Martins Neto, F.L.; Peralta-Antonio, N.; de Paula Pimenta, M.; Rocha, S.B.F.; Silva Santos, R.H. Continuous Application of Compost and Green Manure Improves the Plant Growth and Productivity of Coffee Trees. *Commun. Soil Sci. Plant Anal.* **2022**, *53*, 987–999. <https://doi.org/10.1080/00103624.2022.2039174>.
95. Li, W.; Li, M.; Li, S.; Zhang, Y.; Li, X.; Xu, G.; Yu, L. Function of Rice High-Affinity Potassium Transporters in Pollen Development and Fertility. *Plant Cell Physiol.* **2022**, *63*, 967–980. <https://doi.org/10.1093/pcp/pcac061>.
96. de Magalhães, W.; Araújo, S.C.; Cecon, P.R.; Nogueira, M.A.; Martinez, H.E.P. Root Growth, Leaf and Root Chemical Composition along Coffee Fruit Development. *J. Soil Sci. Plant Nutr.* **2025**, *25*, 1968–1981. <https://doi.org/10.1007/s42729-025-02249-7>.
97. Rogiers, S.Y.; Page, J.T.; Thapa, M.; Jeong, K.; Rose, T.J. Temporal Accumulation and Partitioning of Mineral Nutrients in Developing Macadamia Fruit. *Horticulturae* **2026**, *12*, 522. <https://doi.org/10.3390/horticulturae12050522>.
98. de Moraes, F.R.P.; Catani, R.A. Absorption of Mineral Elements by Coffee Berries during Their Formation. *Bragantia* **1964**, *23*, 331–336. <https://doi.org/10.1590/S0006-87051964000100026>.

99. de Lima Filho, O.F.; Malavolta, E. Studies on Mineral Nutrition of the Coffee Plant (*Coffea arabica* L. Cv. Catuaí Vermelho): LXIV. Remobilization and Re-Utilization of Nitrogen and Potassium by Normal and Deficient Plants. *Braz. J. Biology*. **2003**, *63*, 481–490. <https://doi.org/10.1590/S1519-69842003000300014>.
100. Akter, S.; Kamruzzaman, M.; Khan, M.Z.; Amin, M.S. Enhanced Potassium Fertilization Improved Rice (*Oryza sativa*) Yield and Nutrient Uptake in Coastal Saline Soil of Bangladesh. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 1884–1895. <https://doi.org/10.1007/s42729-023-01144-3>.
101. Karim, A.; Hifnalisa, H.; Jufri, Y.; Hidayanti, H.; Rosmaiti, R. Improvement in the Physical Quality of Genotype G1 Arabica Coffee Beans as a Result of Applying Rice Husk Ash and KCl Fertilizer. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1356*, 012020. <https://doi.org/10.1088/1755-1315/1356/1/012020>.
102. Moon, J.-K.; Shibamoto, T. Role of roasting conditions in the profile of volatile flavor chemicals formed from coffee beans. *J. Agric. Food Chem.* **2009**, *57*, 5823–5831. <https://doi.org/10.1021/jf901136e>.
103. Vinecky, F.; Davrieux, F.; Mera, A.C.; Alves, G.S.C.; Lavagnini, G.; Leroy, T.; Bonnot, F.; Rocha, O.C.; Bartholo, G.F.; Guerra, A.F.; et al. Controlled Irrigation and Nitrogen, Phosphorous and Potassium Fertilization Affect the Biochemical Composition and Quality of Arabica Coffee Beans. *J. Agric. Sci.* **2017**, *155*, 902–918. <https://doi.org/10.1017/S0021859616000988>.
104. Kulapichitr, F.; Borompichaichartkul, C.; Fang, M.; Suppavorasatit, I.; Cadwallader, K.R. Effect of Post-Harvest Drying Process on Chlorogenic Acids, Antioxidant Activities and CIE-Lab Color of Thai Arabica Green Coffee Beans. *Food Chem.* **2022**, *366*, 130504. <https://doi.org/10.1016/j.foodchem.2021.130504>.
105. Sunarharum, W.B.; Williams, D.J.; Smyth, H.E. Complexity of Coffee Flavor: A Compositional and Sensory Perspective. *Food Res. Int.* **2014**, *62*, 315–325. <https://doi.org/10.1016/j.foodres.2014.02.030>.
106. Freitas, V.V.; Borges, L.L.R.; Castro, G.A.D.; Almeida, L.F.; Crepalde, L.T.; dos Barros Kobi, H.; Vidigal, M.C.T.R.; dos Santos, M.H.; Fernandes, S.A.; Maitan-Alfenas, G.P.; et al. Influence of Roasting Levels on Chemical Composition and Sensory Quality of Arabica and Robusta Coffee: A Comparative Study. *Food Biosci.* **2024**, *59*, 104171. <https://doi.org/10.1016/j.fbio.2024.104171>.
107. Cardoso, W.S.; Dias, S.R.; Coelho, V.S.; Pereira, L.L.; Fioresi, D.B.; Pinheiro, F. de A. Maillard Reaction Precursors and Arabica Coffee (*Coffea arabica* L.) Beverage Quality. *Food Humanit.* **2023**, *1*, 1–7. <https://doi.org/10.1016/j.foohum.2023.01.002>.
108. Alsafra, Z.; Kuuliala, L.; Scholl, G.; Saegerman, C.; Eppe, G.; De Meulenaer, B. Characterizing the Formation of Process Contaminants during Coffee Roasting by Multivariate Statistical Analysis. *Food Chem.* **2023**, *427*, 136655. <https://doi.org/10.1016/j.foodchem.2023.136655>.
109. Dong, R.; Zhu, M.; Long, Y.; Yu, Q.; Li, C.; Xie, J.; Huang, Y.; Chen, Y. Exploring Correlations between Green Coffee Bean Components and Thermal Contaminants in Roasted Coffee Beans. *Food Res. Int.* **2023**, *167*, 112700. <https://doi.org/10.1016/j.foodres.2023.112700>.
110. Duan, S.; Yu, L.; Dong, J.; Du, Z.; Liu, S.; Yin, H.; Li, Y.; Shen, Y.; Yu, R.; Xue, C.; et al. Biomimetic Fermentation Reshapes Precursor Pools to Drive Synergistic Roasting Reactions and Enhance Coffee Flavor Complexity. *Foods* **2026**, *15*, 849. <https://doi.org/10.3390/foods15050849>.
111. Salvador, H.P.; Semedo, J.N.; Rakocevic, M.; Ramalho, J.C.; Partelli, F.L. Dynamics of Dry Matter Accumulation in the Berries, Beans, and Husks of Six *Coffea canephora* Genotypes during Fruit Maturation. *Exp. Agric.* **2025**, *61*, e26. <https://doi.org/10.1017/S0014479725100185>.
112. Li, Z.; Zhou, B.; Zheng, T.; Zhao, C.; Shen, X.; Wang, X.; Qiu, M.; Fan, J. Integrating Metabolomics and Proteomics Technologies Provides Insights into the Flavor Precursor Changes at Different Maturity Stages of Arabica Coffee Cherries. *Foods* **2023**, *12*, 1432. <https://doi.org/10.3390/foods12071432>.
113. León-Burgos, A.F.; Sáenz, J.R.R.; Quinchua, L.C.I.; Unigarro, C.A.; Osorio, V.; Khalajabadi, S.S.; Balaguera-López, H.E. Varying Fruit Loads Modified Leaf Nutritional Status, Photosynthetic Performance, and Bean Biochemical Composition of Coffee Trees. *Sci. Hortic.* **2024**, *329*, 113005. <https://doi.org/10.1016/j.scienta.2024.113005>.

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